AN INVESTIGATION OF THE EFFECTS OF SYMMETRY IN INDUSTRIAL ASSEMBLY OPERATIONS

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ABSTRACT

Schetky, Malcolm Oliphant, M. S. (Industrial Engineering), Purdue University, June 1959. An Investigation of the Effects of Symmetry in Industrial Assembly Operations. Major Professor: Hewitt H. Young

The purpose of this investigation was to study the effect of symmetry upon the time required for the positioning and assembly of mating parts which had various degrees of symmetry. "Degrees of symmetry" was defined as the number of ways a part could be oriented about its axis while being assembled into a mating part.

Fourteen operators performed the experiment, which consisted of a repetitive assembly operation, with nine differently shaped parts, each having a different number of degrees of symmetry. The operation was performed with one shape at a time in an apparatus requiring transport loaded (TL), position (P) and assemble (A) therbligs followed by disassembly and discard of the part.

The data were subjected to the analysis of variance technique, and it was shown that the symmetry of the parts had a significant effect upon the times required for each of the above therbligs. Through the use of a regression analysis, the average time for position-and-assembly (P+A) was shown to have a linear relationship to degrees of symmetry. It was further suggested that 12 degrees of symmetry may be the maximum number which need be considered, and that parts having 12 or more degrees of symmetry can be considered to be symmetrical.

AN INVESTIGATION OF THE EFFECTS OF SYMMETRY IN INDUSTRIAL ASSEMBLY OPERATIONS

INTRODUCTION AND PURPOSE

In a study of predetermined time systems, only a few were found to give consideration to the symmetry of objects. The presentation of data in most systems neglected the symmetry of parts in tabulating times for position and assembly operations. Some systems which have considered it, did so only by the addition of a degree of control.

The Methods-Time-Measurement[1] or MTM system did present a three factor table for Position elements based on symmetry, class of fit and ease of handling. For the factor of symmetry, objects are classified as symmetrical, semi-symmetrical or non-symmetrical. These are defined as follows.

> Symmetrical: Object can be positioned in an indefinite number of ways about the axis that coincides with its direction of travel.
> Semi-symmetrical: Object can be positioned in several ways about the axis that coincides with the direction of travel.
> Non-symmetrical: Object can be positioned in only one way about the axis that coincides with the direction of travel.[1]

Dr. Ralph Barnes[2], in presenting standard time values for the element of "place", considered the size of the object and the types of grasp as a combined factor versus the amount of positioning required. The standard times established for place were based on data which included transport loaded, position (pre-position), and release load. Symmetry of the part was considered only when it varied the amount of positioning required. Of the several conditions established for the element of place in determining the proper selection of a standard time value, conditions C and D are of interest:

Condition C: Positioning of parts on or into difficult or complicated locations, assemblies, or fixtures requiring the positioning of parts with respect to two definite points, or location in two directions.
Condition D: Positioning is much the same as Condition C but in addition may involve close tolerances, greater care of finishes, three or more points or direction of location, or final application of force to assemble.[2]

Dr. Irwin Lazarus[3], in his discussion of a predetermined-time system, considered symmetry in conjunction with "degrees of restriction". The time values in the table for "position" were dependent upon the number of directions in which accuracy was necessary when locating the piece. Of the two major types of restriction--locational and orientational--only the latter was of interest when concerned with symmetry. All of the six degrees of restriction discussed were considered as adding equally to the time of positioning. An example of possible combinations of degrees of restriction are:

> Five degrees of restriction could be represented by the positioning of a cube into a congruent hole only slightly larger than that cube. Locationally, the cube would require alignment in the transverse (sideways) direction and in the forward and backward direction, but it would be free vertically. Orientationally the cube would be restricted in all three degrees of roll, pitch, and yaw.[3]

A symmetrical object such as a cylinder was considered by Lazarus to have only four degrees of restriction as it was free to yaw about its vertical geometric axis (simple rotation).

Symmetry was not considered but may be a factor in another aspect of time study--that of rating. Dr. Marvin Mundel[4], in making secondary adjustments to original observed data, considered the factor of eye-hand co-ordination as one adjustment and, in so doing, made allowances only for the tolerance of placement. He stated that experiments had shown the times for extremely simple cycles were increased by 11 to 25 per

cent when eye-hand co-ordination was radically increased. A possible factor which affected the co-ordination required could be the symmetry of a part. Any object which is not symmetrical necessitates additional hand control in assembly operations.

It was the purpose of this study to determine if symmetry (1) can be classified by specific and less all-encompassing terms, and (2) should be given greater consideration in assembly operations. To accomplish this, the term "degrees of symmetry" was introduced and defined as the number of ways that an object could be oriented about its axis while being assembled into a mating part. For example, a cylindrical object, which by MTM standards was symmetrical, would have infinite degrees of symmetry; and a square, which in MTM is classified as semi-symmetrical, would have four degrees of symmetry. Any object which was non-symmetrical would have only one degree of symmetry.

With an aim towards simplification of the experiment and its later analysis, the variables considered were reduced to a minimum. Those variables which could not be eliminated were randomized or neglected as being insignificant. Some variables could not be controlled at all for the experiment. These included the emotional state and the motivation of the operators and their activities, both mental and physical, just prior to the experiment. It was recognized that the operators selected did not necessarily represent a random sample of the industrial population. They were, however, chosen at random from a group of graduate students enrolled in the Industrial Engineering courses at Purdue University. They were all familiar with time and motion study principles, and it was hoped that this would serve to provide the proper motivation.

The variables considered were the operators and the symmetry of the parts. Other possible variables such as type and condition of grasp, clearance, motion path and direction of transport were standardized and were so selected as to be as near the "ideal" as possible. Handles were attached to each male profile part and provided a three finger and thumb grasp which was easy to pick up and in most cases provided maximum control[2]. The condition of grasp was the best possible in that the parts were pre-positioned for grasp and the grasp was not hampered by other objects in contact with the object being grasped[2]. The location of all of the assembly elements were in the preferred section of the work area, particularly where visual direction was required[4]. Due to the light weight of the parts, which was equalized for the different profiles, weight was not considered as a separate factor. Total weight of a part and handle was 3 1/2 ounces.

It was an hypothesis of this study that the symmetry of a part was a quantitative variable which could be used to select a proper time value, in pre-determined time systems, for position and assembly operations. This symmetry variable might also be a factor to consider in rating the difficulty of some assembly operations. Some difficulty was expected in determining the exact division between the end of the position therblig and the beginning of the assemble therblig. In that these therbligs often occurred in conjunction with each other, it was believed that more emphasis should be placed on the analysis of data for the times of position-and-assemble therbligs (P+A). The terminal points at the beginning of position and at the end of assembly were determinable to a much greater accuracy, and conclusions based on the combined times (P+A)

were expected to be more reliable than if based on times for the individual elements of Position (P) and Assembly (A). If it could be shown that there was a significant difference in the times for position-and-assembly of mating parts having different degrees of symmetry, then a regression curve might be found which would establish a positive relationship between position-and-assembly time and the degree of symmetry of the mating parts.

APPARATUS

The apparatus was designed to provide for the measurement of the times to complete four therbligs in a repetitive assembly operation. All of the items of equipment used in this experiment are listed with complete specifications in Appendix E. Those therbligs timed were Transport Loaded (TL), Position (P), Assemble (A), and Disassemble (DA). Other therbligs in the cycle were not measured, although an overall time could have been determined for them. To measure the elapsed times for the various therbligs, several detection devices were connected to three solenoids of a tape-recording kymograph[5] (Plate I). When actuated by external electrical contacts, the solenoids cause individual pens to jog approximately one-quarter of an inch transverse to the movement of the kymograph tape. The kymograph drive is powered by a constant speed motor which pulls the tape under the pens at a constant velocity of 562 inches per minute (1 inch in 0.0018 minute). Times for various therbligs are determined by measuring the distance between deflections of the ink traces. To measure these distances a transparent scale calibrated in 0.0001 minute may be laid over the ink traces and the times determined as indicated in Figure 1.

An 18-inch turntable (Plate II), powered by a variable speed drive and turning at 6.8 rpm, was used to move the male profile parts from the release point at the right hand end of a table slot to the pickup point at the left hand end with respect to the operator's view. The turntable was so placed beneath the table slot that as it turned, the parts bumped against the slot edge before coming to rest against a gate at the left hand end of the slot (Plate III). Bumping the slot edge caused the

[illegible]

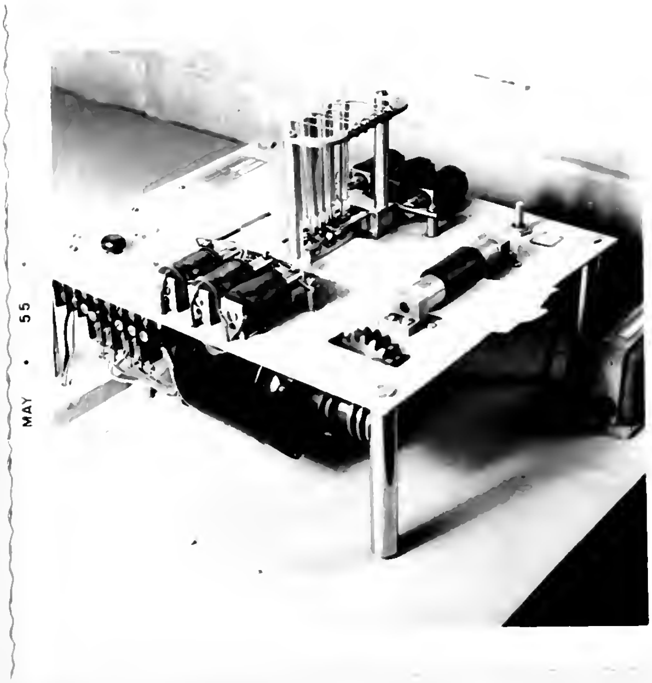
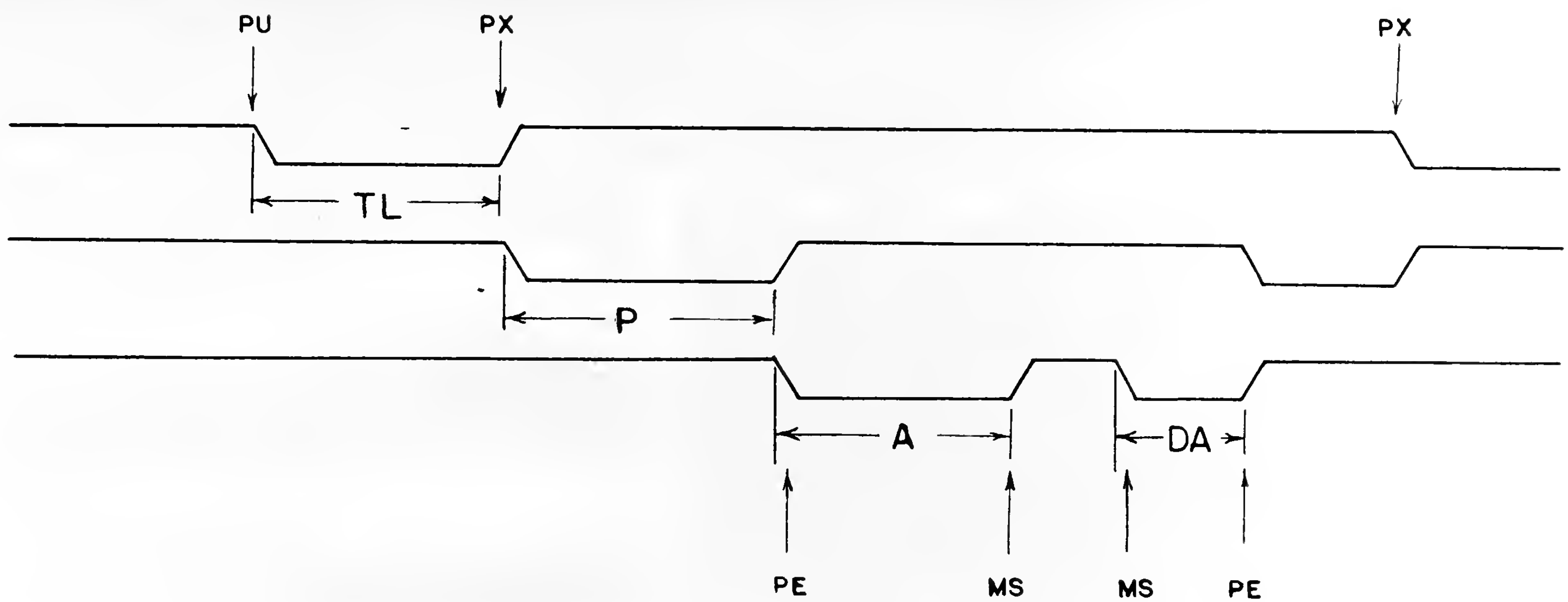


PLATE I

KYMOGRAPH



THERBLIGS

TL — TRANSPORT LOADED
P — POSITION
A — ASSEMBLE
DA — DISASSEMBLE

DEVICE CAUSING DEFLECTIONS

PU — PICKUP DEVICE
PX — PROXIMITY DEVICE
PE — PHOTOELECTRIC RELAY
MS — MICROSWITCH

FIGURE I

REPRODUCTION OF KYMOGRAPH TAPE

PLATE II

EQUIPMENT ON TABLE SHELF

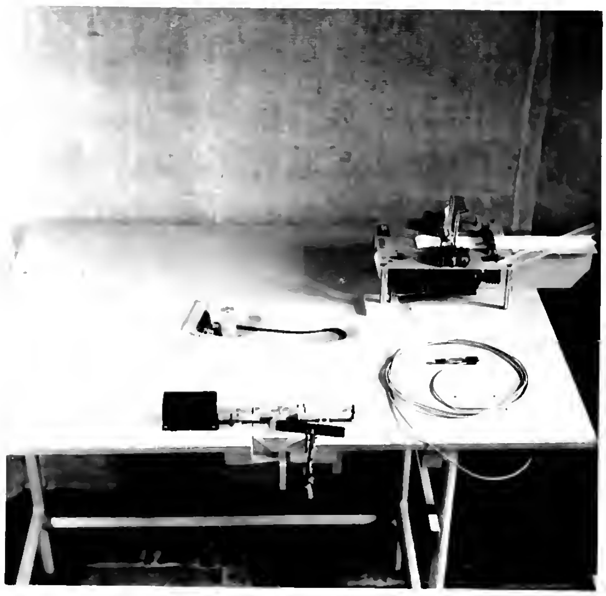


PLATE III

TOP VIEW OF APPARATUS
FROM
OPERATOR'S STATION

profile parts to rotate and served to randomize the orientation of the profiles. The pickup point and release point were 14 inches apart and equidistant (16 inches) from the assembly point.

To determine the start of the TL therblig, a gate arrangement was used. The pressure of a part being pushed by the turntable against the gate caused it to swing and actuate a microswitch behind it. As a part was picked up, the pressure of the microswitch spring moved the gate to its original position. In that the normally open contact of this microswitch was used, it closed when a part pushed against the gate and thus energized solenoid No. 1 of the kymograph (Figure 2). When the part was removed at the start of the TL therblig, the microswitch contacts opened as the gate moved to its normal position. This de-energized the solenoid circuit again causing a deflection in the ink trace and indicated the start of a cycle.

The end of the TL therblig was also the start of the P therblig, thus this event was signaled by the same device. In that positioning was assumed to begin when the part was close to the assembly point, a proximity (PX) measuring device was developed. This consisted of a bar magnet clamped to the table and a Glaswitch* taped to the operator's wrist (Plate IV). The Glaswitch is a dry-reed switch sealed in a glass capsule which is actuated by an external magnetic field (Plate V). The magnet was adjusted positionwise so that the Glaswitch closed as the operator moved his arm over the magnet and the male profile part was at a distance of 1 1/2 inches from the assembly point. When actuated, the

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*Glaswitch -- E-5600 Magnetic Dry-Reed Switch developed by the Revere Corporation of America, Wallingford, Connecticut.

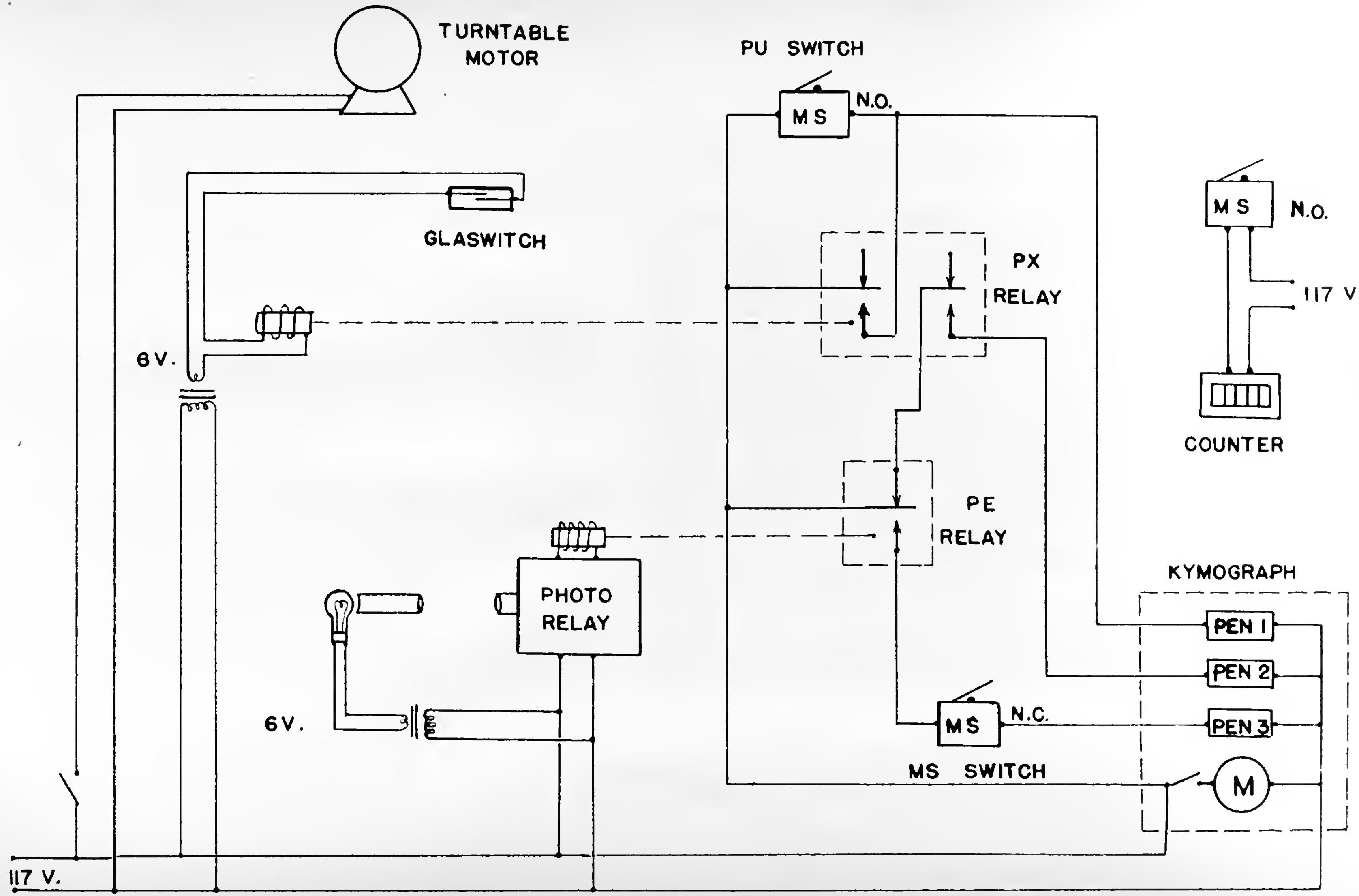

FIGURE 2
WIRING DIAGRAM FOR ELECTRIC DEVICES

PLATE IV

ASSEMBLY AREA

PLATE V

GLASWITCH
AND
PROXIMITY DEVICE

Glaswitch completed the circuit to a six volt DPDT proximity relay. The normally open contacts of one pole of the PX relay were connected to pen No. 1 of the kymograph and caused it to be deflected as long as the operator's hand was near the magnet. The normally open contacts of the other pole of the PX relay were connected in series with the normally closed relay contacts of a photoelectric (PE) relay to pen No. 2 of the kymograph. When the PX relay was actuated, it completed this circuit and caused a deflection in trace No. 2 which indicated the beginning of the P therblig. At the same instant it completed the circuit to pen No. 2, it completed the circuit to pen No. 1 and caused a deflection in trace No. 1 which indicated the completion of the TL therblig.

The end of the P therblig was signaled by the actuation of the photoelectric relay mentioned above. When actuated, this opened the circuit to pen No. 2 and allowed it to return to its original position. The PE relay was actuated by the interruption of a light beam directed across the top of the female profile part mounted in a fixed position at the assembly point (Plate IV). At the same instant that the normally closed contacts of the SPDT PE relay opened the circuit to pen No. 2, the normally open contacts completed the circuit to pen No. 3 and caused it to deflect. This gave an indication of the beginning of the assembly time. As the male profile part was completely assembled into the female mating part, the completion of the assembly therblig was indicated by depressing a microswitch (Plate VI). The normally closed contacts of this microswitch were placed in series with the normally open contacts of the PE relay such that, when the microswitch was

[illegible]
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[illegible]
[illegible]
[illegible]
[illegible]
[illegible]
[illegible]
[illegible]

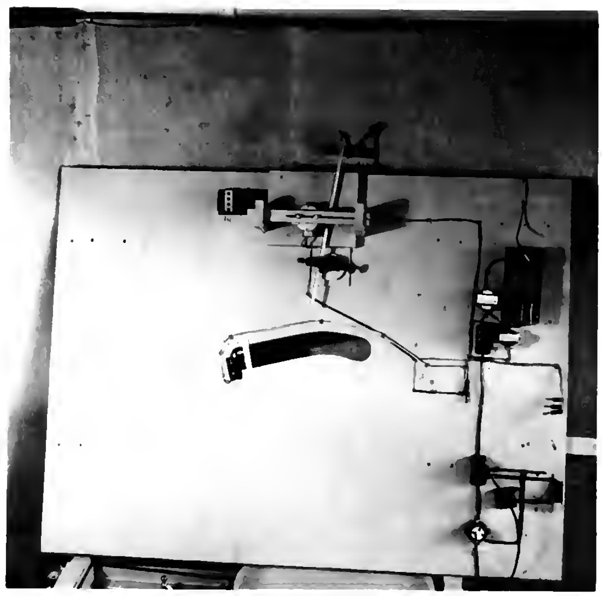

PLATE VI

ELECTRICAL CONNECTION
UNDERSIDE OF TABLE-TOP

depressed, the circuit was broken and pen No. 3 returned to its normal position.

The various devices and the kymograph pens worked in the reverse order to that described above as the part was disassembled and moved to the release point on the turntable.

A solenoid-operated counter, used to keep count on the number of cycles performed by the operator, was actuated by a normally open SPST microswitch situated to the right of the kymograph (Plate VII). The observer watched the recording tape to see that all circuits were functioning properly and depressed the counter-switch for each completed cycle, which advanced the counter one digit.

Figure 1 shows a sample reproduction of the record made by the solenoid-operated pens on the kymograph tape. The pickup device (PU) caused a deflection in line No. 1 only. The proximity device (PX) actuated pens No. 1 and 2 and thus caused deflections in both lines No. 1 and 2. The photoelectric relay (PE) was connected to both pens No. 2 and 3 and caused the deflections indicated. The microswitch (MS) at the base of the mating parts affected only line No. 3. The times for the therbligs TL, P and A were measured as indicated.

All male profile parts had an overall length of 1 1/2 inches and could be inscribed in a circle 1 1/2 inches in diameter. This was done to keep their overall outside dimensions approximately equal. These parts were made of aluminum to keep their weight at a minimum. The total weight (3 1/2 ounces) of each of the parts was equalized by the removal of material from the interior of the heavier parts. The female mating parts were constructed from a block of oak 4 x 3 7/8 inches with a center profile section of plastic steel. The plastic steel is a

PLATE VII

TOP VIEW OF APPARATUS
FROM
OBSERVER'S STATION

combination of approximately 80% steel and 20% of a newly developed plastic under the trade name of Devcon.* While being molded, it was of the consistency of modeling clay and became an extremely strong and rigid metallic piece after approximately two hours hardening time. A clearance allowance of 0.0034 inches, to provide an A.S.A. Class 1 Loose Fit between the male and female parts, was obtained by wrapping the male profile parts with two layers of cloth tape before using them as patterns in forming the profile section of the female parts from plastic steel.

*Devcon — "The Plastic Steel" developed by Chemical Development Corporation, Danvers, Massachusetts.

PROCEDURE

In order to determine the effect of symmetry upon position and assembly therblig times, 9 profiles were investigated (Plate VIII). The primary group consisted of 6 parts having decreasing degrees of symmetry. Parts in the secondary group had only one degree of symmetry and were considered to be non-symmetrical.

Group	Part No.	Profile (Cross Section)	Degrees of Symmetry
Primary	1	Circle	∞
	2	Hexagon	6
	3	Square	4
	4	Equilateral triangle	3
	5	Rectangle	2
	6	Rectangle with rounded corner	1
Secondary	7	Circular with keyway	1
	8	Circular with key	1
	9	Circular with 4 pins in base	1

The operator was first asked to read the "Instructions to Operators" (Appendix A). Questions were then answered and the equipment was demonstrated. Prior to recording any data the operator was given a five minute training period, and for this all operators used Part No. 1, with the circular cross section. Before proceeding, all operators expressed the feeling of being familiar with the equipment and its operation cycle.

The various profiles were presented in a random order (Appendix B) to minimize any effects of learning and fatigue upon the times measured. In presenting a particular profile, the female mating part was positioned; one male part was placed in it, and a duplicate male part was placed on the turntable. When the latter had reached the left end of the slot, the operator was instructed to start the run. So that the operator could establish a steady performance rate, he was allowed to complete ten

PLATE VIII

PROFILE PARTS

cycles before the kymograph was energized. The counter was used to insure that at least fifteen cycles were recorded. The kymograph was then stopped and the next set of parts placed in position. If an operator fumbled, a mark was made on the kymograph tape to so indicate, and that particular cycle was not considered in analyzing the data.

Operators occupied a standing position in front of the assembly area. They were so positioned that their forearms followed a straight line directly over the assembly area and the magnet. This was necessary to insure proper operation of the proximity device.

The entire experiment required, on the average, thirty minutes per operator. This was divided into ten minutes for the instruction and training period and the remainder for actual operation to collect data. Each profile phase took approximately two minutes to obtain the data and exchange parts for the following phase.

The data were recorded (Appendix C) by measurement of the times for the three therbligs of interest in the investigation. All times for the Transport Loaded (TL), Position (P), and Assemble (A) therbligs were recorded to the nearest 0.0001 minute. The data was summarized for each therblig by computation of the range and average values for each profile and for each operator (Appendix C, Tables 2 to 5). In a few cases only thirteen or fourteen valid readings were obtained. To equalize the number of readings in each cell (a cell was considered to be a combination of the ith operator and the jth profile), it was decided to consider only the middle ten readings (Appendix C, Tables 6 to 19). The first two readings were neglected to remove the effect of any distraction of the operator's attention which might have resulted when

the kymograph was started. The last three readings were not considered so as to equalize the number of readings in each cell, which simplified later computations. The range was taken as the difference between the minimum and the maximum time values of the ten readings considered.

The data for each of the three therbligs were tested for significant difference between the means by the Analysis of Variance procedure described by Dixon and Massey[6] for a two-way classification of data.

Further analysis was performed to determine the type of regression[6] for position-and-assemble times (P+A) on degrees of symmetry. The regression curve was based on the data for parts Nos. 2, 3, 4, 5, and 6 only and extrapolated to determine what number of degrees of symmetry corresponded with the time value obtained for the symmetrical part (cylindrical profile).

All data in appendices were recorded as MINUTES x 10^{-4}.

RESULTS AND CONCLUSIONS

The results of this experiment as tabulated in the Summary Data, Appendix C, Tables 2 to 5, indicated that the average times of the transport loaded (TL), position (P), and assemble (A) therbligs and for the combined times for position-and-assembly (P+A) were all affected significantly by the symmetry of the part being assembled. The analysis of variance was limited to the determination of whether that variation attributable to the number of degrees of symmetry of a part was significant. The results of the F test were as follows.

Therblig	F_c	F_α	α
TL	[illegible]	[illegible]	.010
P	[illegible]	[illegible]	.025
A	[illegible]	[illegible]	.010
P+A	17.20	[illegible]	.010

The analysis of variance technique, developed to facilitate the analysis and interpretation of data from laboratory experiments, requires certain assumptions about the data to be studied. One of these is that all of the cell variances are homogeneous. This hypothesis of homogeneity of variance was tested by comparing the range of values in each cell to certain control limits. If the ranges for all cells are within the 3-sigma control limits, the assumption of homogeneous variances may be considered valid (Appendix I, Table 20). In making this test on the sets of summary data for the four therbligs (Tables 2 to 5), the ranges of time values for several operators for part No. 9 were far outside the 3-sigma control limits. This was due in part to a change in method introduced by some operators during the TL therblig. The variation consisted of a slight hesitation while the part was swung sideways to observe the orientation of the prongs and

a more definite pre-positioning during the TL therblig. The average times for part No. 9 were in some cases approximately double those for the other parts. Due to its construction, this part required additional control and resulted in there being two distinct phases during the assembly (A) therblig. In the first phase the prongs were assembled into the upper section of the mating part, and this was accomplished relatively easily. The second phase of positioning and assembly of the prongs into their mating holes provided considerable difficulty for some operators. For the above reasons, part No. 9 was not considered to be comparable to the other parts and its data were not used in the remainder of the analysis.

New average values of the range ($\overline{R}$) were found and the control limits recomputed (Table 20). The remaining parts were felt to satisfy the requirement for homogeneity of variance and the analysis of variance was performed on parts Nos. 1 to 8.

In that only the average value, $\overline{Y}$, was used in the analysis (one replication per cell), no separate measure of the error term was obtained. Therefore, no test was made for the significance of the other sources of variation, and the components of variance were not determined. The Expected Mean Squares were as follows:

Source of Variation	Expected Mean Square
O [Random Factor]	$\sigma_e^2 + 10n\,\sigma_o^2$
P [Fixed Factor]	$\sigma_e^2 + n\,\sigma_{op}^2 + 30n\,\sigma_p^2$
OxP (Error)	$\sigma_e^2 + n\,\sigma_{op}^2$

where n was the number of readings per cell used to compute the average time values $\overline{Y}_{ij}$. An estimate of σ_e^2 was obtained by considera-

tion of the factor d_2 for the central line of the control chart for ranges[7]: $\sigma_e = \frac{\bar{R}}{d_2}$

By application of the regression theory, the curve for the regression of time to position-and-assemble (P-A) on degrees of symmetry was determined. Computations were based on the primary group of parts with the exception of part No. 1. This symmetrical part had infinite degrees of symmetry and it was not possible to determine a reasonable number of degrees of symmetry to be assigned for the regression analysis. An analysis of variance on this set of data again showed the effect of degrees of symmetry to be significant, and the percentage of the variation of times which could be accounted for by a regression curve was 34%. The regression line developed was extrapolated to determine what number of degrees of symmetry could be used to approximate those of a symmetrical part. This was determined by the intersection of the regression line and a line drawn through the time value obtained for the true symmetrical part (Figure 3). It was felt that the times determined for parts having 1 and 2 degrees of symmetry were lower than they should be. It is believed that this was due to the parts being partially oriented at the pick-up position which reduced the total time required. It is suggested that future experiments investigating this phenomenon introduce more position randomization of the orientation of both the male profile parts and the female mating part.

The results of the analysis of variance and the regression analysis indicated that the time required for the therbligs which comprised the assembly operation were affected by the degrees of symmetry. The

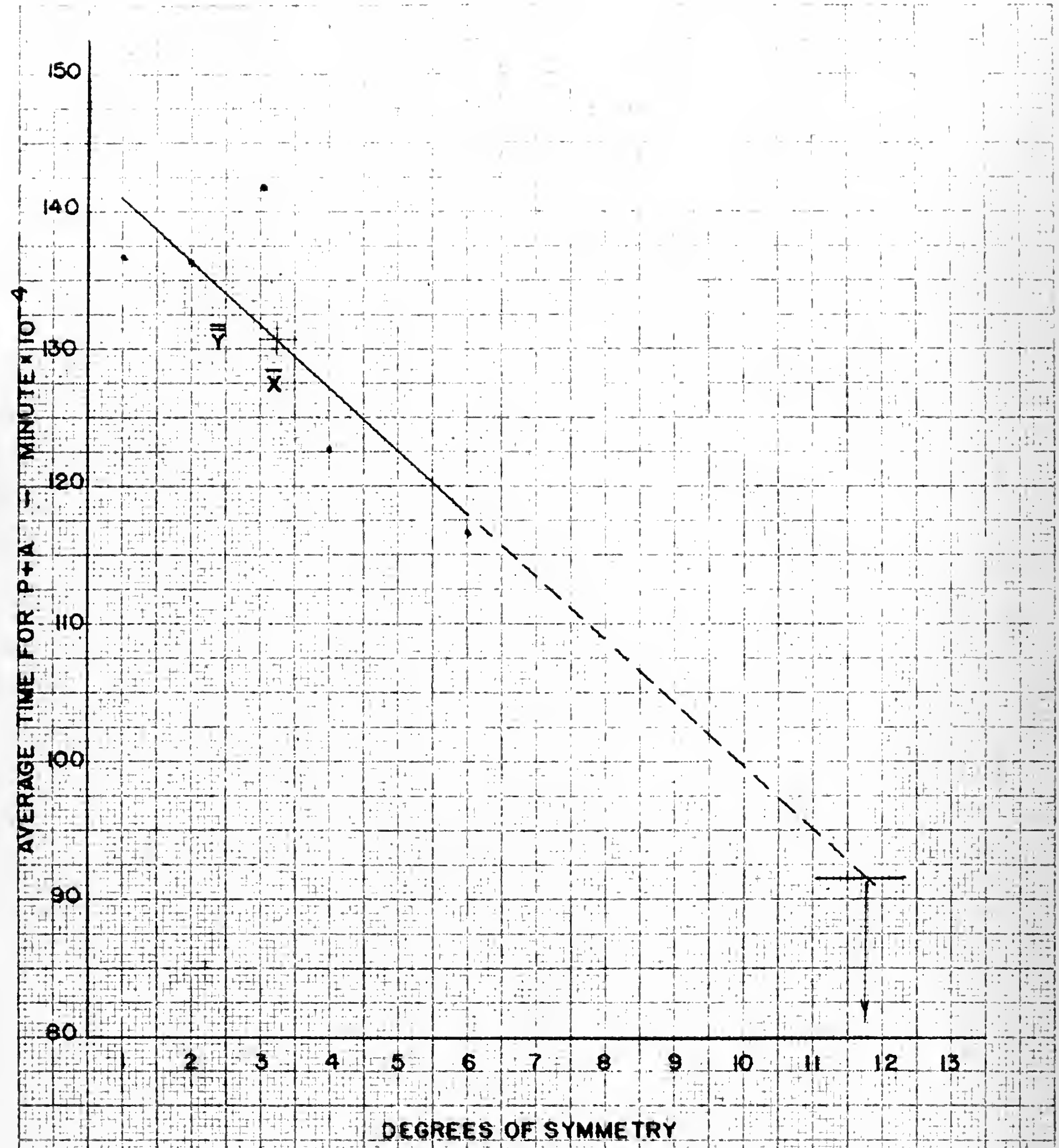

FIGURE 3
REGRESSION CURVE

regression of times to position-and-assemble (P+A) on degrees of symmetry was shown to be linear, and a regression curve of the form $\hat{Y}_x = b_0 + b_1 (X_j - \bar{X})$ was found to be the "best fitted" curve based on the data for parts which had 1, 2, 3, 4, and 6 degrees of symmetry. For these parts the linear regression line accounted for 24% of the variation.

If it can be assumed that the linear regression trend would hold for parts having greater than 6 degrees of symmetry, the extrapolation performed indicates that the time determined for the symmetrical part might also be expected for a part having approximately 12 degrees of symmetry. It may therefore be possible to consider any part having 12 or more degrees of symmetry as being symmetrical for the purposes herein discussed, and 12 degrees of symmetry are suggested to be a possible maximum number which need be considered in further investigations.

It is noted that the difference in the average times to position-and-assemble (P+A) parts having one and infinite degrees of symmetry was 45.2×10^{-4} minute, and the difference in the average times for parts having one and six degrees of symmetry was 20.2×10^{-4} minute. Thus the percentage increase in time to position and assemble a part having only one degree of symmetry over the time required for a symmetrical part was approximately 50%.

BIBLIOGRAPHY

BIBLIOGRAPHY

1. Maynard, H. B., Stegemerten, G. J., and Schwab, J. L., Methods-Time Measurement, McGraw-Hill Book Company, Inc., New York, 1948

2. Barnes, R. M., Motion and Time Study, John Wiley and Sons, Inc., New York, 1949

3. Lazarus, I. P., A System of Predetermined Human Work Times, Ph.D Thesis, Purdue University, 1952

4. Mundel, M. E., Motion and Time Study, Prentice-Hall Inc., New York, 1950

5. Barnes, R. M., and Mundel, M. E., A Study of Hand Motions Using the Photoelectric Cell and the Kymograph, University of Iowa Studies in Engineering, Bulletin 12.

6. Dixon, W. J., and Massey, F. J. Jr., Introduction to Statistical Analysis, McGraw-Hill Book Company, Inc., New York, 1951

7. ASTM Committee E-11, ASTM Manual on Quality Control of Materials, American Society for Testing Materials, 1955

GENERAL REFERENCES

Eisenhart, C., The Assumptions Underlying the Analysis of Variance, Biometrics, Vol. 3, No. 1, March, 1947

Holmes, W. G., Applied Time and Motion Study, The Ronald Press Company, New York, 1945

Parton, J. A. Jr., Motion and Time Study Manual, Conover-Most Publications, Inc., New York, 1952

Presgrave, R., The Dynamics of Time Study, McGraw-Hill Book Company, Inc., 1945

APPENDICES

APPENDIX A

INSTRUCTION TO OPERATORS

This experiment is designed to investigate the effects of symmetry in industrial assembly operations. To do this, you will be presented nine different parts which you are asked to assemble as described below. Prior to recording any cycles, you will be given a five minute practice session. This will enable you to become familiar with the equipment, its operation, and to establish a smooth rhythm. After the practice session you will be given a short rest period while the equipment is adjusted.

Please read the instructions and if there are any questions, I shall answer them, demonstrate the procedure and explain the operation of the equipment.

Position 1. Stand directly in front of the assembly area and place your left hand on the table. Keep left hand on the table at all times while conducting the experiment.

2. Assist observer in attaching proximity device to wrist and pinning cord to sleeve.

3. Grasp part indicated and hold it while magnet is adjusted.

Procedure 1. Grasp part using only finger tips and thumb tip of right hand.

2. Move part to assembly area, position it as necessary and assemble it into the mating bushing in front of you.

3. After part strikes bottom, release it momentarily, then re-grasp, lift it out and move to right end of slot.

4. Place part on the turntable and release it. (Be sure part is upright and will not topple.)

5. Move empty hand to left end of slot, grasp other part and repeat cycle.

Precautions

1. Work as rapidly as possible maintaining a smooth and rhythmical pattern of motions.

2. Do not drop part into mating part--assemble by hand and then release it momentarily.

3. Place part on turntable naturally at extreme right end. Do not drop it.

4. In moving from Pick-Up part to Assembly Area, keep arm straight. Align part by use of fingers and wrist rather than swinging arm to side.

NOTES: The only times being measured are the

Transport Loaded

Position

and Assemble

Other portions of the cycle are neglected so that any time-lag while discarding the part will not disrupt the readings.

Thank you immensely for your co-operation and assistance in this experiment.

M. O. Schetky

[illegible]
[illegible]

[illegible]
[illegible]
[illegible]
[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

APPENDIX B

Table 1--Part Sequence

a. Sequence of parts determined from table of random numbers.

b. Parts numbered as follows:

Part No.: 1 2 3 4 5 6 7 8 9

Shape:

Part Sequence

Operator No.	1	2	3	4	5	6	7	8	9
A	1	3	9	4	7	5	8	6	2
B	7	4	8	9	2	6	1	3	5
C	6	3	9	7	5	8	2	1	4
D	1	3	7	8	5	2	6	9	4
E	3	5	1	8	6	4	2	9	7
F	6	8	5	3	7	9	2	4	1
G	8	5	9	3	2	7	4	1	6
H	8	7	6	5	2	4	1	3	9
I	6	7	9	4	8	3	2	5	1
J	4	9	8	3	6	2	1	5	7
K	7	8	5	2	9	4	3	6	1
L	4	7	2	8	1	9	5	6	3
M	1	3	6	8	7	4	5	9	2
N	2	4	3	8	9	1	5	7	6

APPENDIX C

Table 2
SUMMARY DATA
FOR
TRANSPORT LOADED (TL) THERBLIG

Profile

OPER		1	2	3	4	5	6	7	8	9
A	R	4	12	10	5	5	28	16	36	45
	Y	42.4	40.9	46.9	43.9	40.0	56.8	50.7	51.9	86.7
B	R	9	16	7	30	13	18	36	17	33
	Y	65.1	64.3	65.7	75.1	59.7	83.3	81.7	86.2	105.9
C	R	14	15	28	15	2	42	16	20	44
	Y	62.6	64.2	72.4	69.5	65.4	90.1	92.0	77.8	89.9
D	R	12	12	15	17	19	19	32	13	15
	Y	64.1	54.7	57.7	65.3	57.7	72.7	67.4	67.2	92.9
E	R	5	21	17	26	16	17	42	14	32
	Y	62.2	72.3	68.4	70.1	72.5	84.2	80.2	93.2	101.4
F	R	13	21	47	15	11	16	32	36	27
	Y	64.4	73.8	67.4	74.5	70.1	74.7	85.6	104.1	122.4
G	R	15	7	9	7	15	25	20	26	31
	Y	61.8	62.1	68.8	63.0	81.1	68.2	75.6	91.0	116.4
H	R	9	10	5	12	12	16	18	6	18
	Y	58.5	61.3	58.2	60.1	57.5	58.3	64.8	73.0	77.4
I	R	6	16	7	9	19	21	23	30	34
	Y	53.7	55.2	51.3	56.6	64.4	82.7	70.4	58.1	111.0
J	R	15	7	10	14	13	14	15	31	78
	Y	42.6	47.3	50.2	49.1	51.5	57.7	60.8	70.0	156.3
K	R	16	46	21	22	20	31	24	16	35
	Y	53.7	71.1	62.4	71.5	73.4	75.3	88.1	78.4	142.9
L	R	13	27	20	21	7	21	24	17	24
	Y	50.2	57.0	62.5	70.3	51.7	62.8	88.4	77.7	121.6
M	R	5	13	20	11	11	9	18	17	30
	Y	73.6	65.7	77.5	64.7	66.0	82.4	69.9	68.9	117.8
N	R	5	9	10	10	12	20	29	22	65
	Y	52.8	49.4	52.9	44.3	58.7	52.4	83.7	69.7	114.0
$R_{.j}$		141	232	226	214	175	297	345	301	511

Table 3
SUMMARY DATA
FOR
POSITION (P) THERBLIG

Profile

OPER		1	2	3	4	5	6	7	8	9
A	R	7	5	12	8	23	14	16	16	13
	Y	14.1	11.9	23.4	27.2	19.5	13.1	14.6	12.3	20.8
B	R	7	14	3	11	14	8	18	15	31
	Y	6.1	16.1	8.1	9.3	13.0	6.9	14.0	11.4	21.8
C	R	15	10	15	21	13	25	18	10	14
	Y	19.0	19.0	18.8	27.7	23.7	15.6	12.7	18.5	21.6
D	R	14	22	31	21	16	29	35	9	11
	Y	26.4	28.8	27.2	17.4	28.0	23.6	32.9	24.1	25.5
E	R	12	18	15	30	15	27	35	11	84
	Y	30.8	31.0	32.2	27.3	25.8	26.0	25.0	21.7	51.0
F	R	38	35	22	15	37	22	21	21	31
	Y	33.4	32.9	34.6	31.8	29.1	29.3	26.7	15.1	34.4
G	R	16	19	9	17	24	21	24	23	21
	Y	15.3	26.9	18.7	19.4	21.7	19.9	35.8	16.0	19.6
H	R	16	13	11	12	11	12	12	8	14
	Y	18.2	20.5	13.8	21.0	24.4	19.4	17.5	14.0	18.6
I	R	5	11	9	15	8	14	16	22	26
	Y	19.5	23.0	22.9	28.1	11.2	16.5	14.5	24.6	32.1
J	R	12	11	11	11	20	23	14	13	86
	Y	16.4	20.7	20.0	23.6	20.7	29.4	23.6	15.7	35.2
K	R	10	23	36	23	18	40	19	21	26
	Y	20.1	18.0	25.7	23.2	10.8	30.8	21.2	20.0	19.2
L	R	28	32	36	39	29	36	23	37	20
	Y	24.8	28.3	19.8	24.1	27.3	28.3	18.8	15.5	16.1
M	R	13	8	18	11	19	17	30	19	29
	Y	26.7	28.8	28.2	35.9	29.1	37.3	26.8	29.1	43.4
N	R	6	16	10	12	15	9	23	19	21
	Y	13.7	20.9	22.0	30.4	19.8	22.9	25.5	16.0	32.3
$R_{.j}$		199	237	238	246	262	297	304	244	427

Table 4
SUMMARY DATA
FOR
ASSEMBLE (A) THERBLIG

Profile

OPER		1	2	3	4	5	6	7	8	9
A	R	22	90	52	92	80	52	56	72	116
	Y	52.7	79.9	93.0	117.6	99.3	83.8	84.4	95.8	122.8
B	R	39	84	71	80	113	102	57	84	104
	Y	78.1	105.1	116.2	149.2	132.0	114.5	78.0	127.1	151.3
C	R	35	70	68	91	109	94	60	67	108
	Y	87.7	112.8	112.5	101.6	124.0	142.1	133.0	125.5	150.8
D	R	26	79	63	114	64	62	96	72	123
	Y	85.6	100.6	110.2	106.9	126.4	112.9	134.8	114.4	123.3
E	R	91	79	85	92	62	108	64	105	54
	Y	71.8	96.4	110.7	145.4	109.8	122.9	119.3	126.4	173.0
F	R	27	38	69	58	67	81	38	57	95
	Y	88.3	131.6	125.3	155.9	153.6	146.9	136.9	147.8	157.5
G	R	53	65	104	100	83	46	58	76	118
	Y	86.8	96.1	119.2	127.5	122.2	110.3	136.5	147.1	107.9
H	R	45	33	69	71	84	96	30	49	78
	Y	69.5	61.9	66.7	84.7	122.1	122.6	97.4	94.5	136.7
I	R	21	44	36	91	40	80	96	53	93
	Y	65.9	99.8	90.3	134.5	97.8	119.4	132.3	114.4	148.0
J	R	31	37	61	67	50	82	74	66	114
	Y	39.4	65.6	62.9	111.0	117.2	92.1	85.1	86.8	121.1
K	R	15	35	78	60	52	48	114	88	70
	Y	65.8	92.6	101.3	121.0	113.9	99.2	111.5	110.9	164.6
L	R	71	44	51	65	71	55	68	51	120
	Y	81.8	79.8	88.3	95.2	92.8	96.8	88.6	83.3	163.1
M	R	16	22	47	91	50	91	55	43	121
	Y	65.9	75.6	102.7	102.2	114.0	129.6	116.6	119.3	151.4
N	R	38	87	67	49	34	42	63	103	97
	Y	61.1	109.8	106.5	83.2	77.9	105.2	104.6	94.8	138.2
$R_{.j}$		530	807	921	1121	959	1039	929	986	1411

Table 5
SUMMARY DATA
FOR
POSITION AND ASSEMBLY (P+A) THERBLIGS

Profile

OPER		1	2	3	4	5	6	7	8	9
A	R	28	91	38	95	103	44	52	74	115
	Y	66.8	91.8	116.4	144.8	118.8	96.9	99.0	108.1	143.6
B	R	37	77	72	80	106	102	60	74	101
	Y	84.2	121.2	124.3	158.5	145.0	121.4	92.0	138.5	151.3
C	R	32	77	88	98	115	93	58	47	101
	Y	106.7	131.8	131.3	129.3	147.7	157.7	145.7	144.0	172.4
D	R	37	79	61	121	65	73	87	77	104
	Y	112.0	129.4	137.4	124.3	154.4	136.5	167.7	138.5	148.8
E	R	94	78	86	117	71	130	100	108	121
	Y	102.6	127.4	142.9	172.7	136.6	148.9	144.3	148.1	224.0
F	R	47	59	71	69	66	75	46	57	117
	Y	121.7	164.5	159.9	187.7	182.7	175.2	163.6	162.9	191.9
G	R	43	65	100	112	82	52	76	77	108
	Y	102.1	123.0	137.9	147.9	143.9	130.2	172.3	163.1	127.5
H	R	53	27	80	71	82	100	39	53	74
	Y	87.7	82.4	80.5	105.7	146.5	142.0	114.9	108.5	155.3
I	R	24	35	34	105	39	76	96	59	86
	Y	85.4	122.8	113.2	162.6	109.0	135.9	146.8	139.0	180.1
J	R	24	50	61	77	51	69	48	64	105
	Y	55.8	86.3	82.9	134.6	137.9	121.5	108.7	102.5	156.3
K	R	12	49	99	71	53	63	125	96	80
	Y	85.9	110.6	127.0	144.2	124.7	130.0	132.7	130.9	183.8
L	R	55	66	46	48	73	58	75	45	122
	Y	106.6	108.1	108.1	119.3	120.1	125.1	107.4	98.8	179.2
M	R	21	26	52	90	63	88	66	44	103
	Y	92.6	104.4	130.9	138.1	143.1	166.9	143.4	148.4	194.8
N	R	38	90	67	48	23	37	74	88	105
	Y	74.8	130.7	128.5	113.6	97.7	128.3	130.1	110.8	170.5
$R_{.j}$		545	819	955	1202	992	1060	1002	963	1442

Table 6

DATA SHEET FOR OPERATOR A

Run	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Min*	Max*	R*	$\overline{Y}$*
P--1/1																			
TL	45	42	43	40	41	44	43	43	43	43	42	42	45	36	--	40	44	4	42.4
P	22	17	17	18	17	16	11	12	11	14	14	11	12	15	--	11	18	7	14.1
A	47	127	65	59	59	52	66	49	45	46	40	46	45	42	--	40	66	22	52.7
P+A	69	144	82	77	76	69	77	61	56	60	54	57	57	57	--	54	82	28	66.8
P--2/9																			
TL	33	35	43	43	40	35	44	36	37	39	47	45	43	--	--	35	47	12	40.9
P	16	12	11	9	13	11	9	15	13	12	10	16	13	--	--	9	16	5	11.9
A	104	67	42	69	56	82	76	44	124	132	105	69	104	--	--	42	132	90	79.9
P+A	120	79	53	78	69	93	85	59	137	144	115	85	117	--	--	53	144	91	91.8
P--3/2																			
TL	44	64	53	48	46	45	50	47	43	49	44	44	43	43	44	43	53	70	46.9
P	20	23	18	23	21	21	18	25	29	27	30	22	21	22	24	18	30	12	23.4
A	85	101	96	93	102	120	115	87	81	68	60	88	103	92	95	68	120	52	93.0
P+A	115	124	114	116	123	141	133	112	110	95	110	110	124	114	119	95	133	38	116.4
P--4/4																			
TL	44	40	45	43	44	43	43	44	44	44	42	47	46	41	43	42	47	5	43.9
P	25	16	28	28	24	25	26	31	27	26	32	25	25	26	22	24	32	8	27.2
A	72	194	158	75	120	120	89	167	95	90	120	142	83	122	106	75	167	92	117.6
P+A	97	210	186	103	144	145	115	198	122	116	152	167	108	148	128	103	198	95	144.8
P--5/6																			
TL	41	38	42	42	41	42	37	39	37	40	39	41	39	41	33	37	42	5	40.0
P	17	23	23	5	15	22	21	23	19	18	21	28	29	28	22	5	28	23	19.5
A	157	83	117	66	68	95	143	75	127	72	84	146	106	181	96	66	146	80	99.3
P+A	174	106	140	71	83	117	164	98	146	90	105	174	135	209	118	71	174	103	118.8
P--6/8																			
TL	45	46	50	54	64	66	50	38	65	58	60	65	55	44	52	38	66	28	56.8
P	15	9	10	18	18	17	13	18	10	9	14	4	14	15	21	4	18	14	13.1
A	88	102	95	62	59	67	97	75	78	104	107	94	128	68	114	59	107	52	83.8
P+A	103	111	105	80	77	84	110	93	88	113	121	98	142	103	135	77	121	74	96.9
P--7/5																			
TL	37	57	48	42	52	49	50	50	49	54	58	55	52	57	56	42	58	16	50.7
P	18	13	18	20	11	14	20	15	8	6	11	23	18	7	14	6	23	17	14.6
A	84	131	94	92	70	84	86	50	76	111	79	102	91	73	76	50	111	56	84.4
P+A	102	144	112	112	81	98	106	65	84	117	90	125	109	80	90	65	117	52	99.0
P--8/7																			
TL	49	47	50	55	58	72	43	45	36	57	54	49	47	48	60	36	72	36	51.9
P	15	11	8	5	18	5	15	23	16	14	12	7	8	22	22	7	23	16	12.3
A	85	78	109	74	135	110	139	81	67	78	81	84	108	92	70	67	139	72	95.8
P+A	100	89	117	79	153	115	154	104	83	92	93	91	116	114	92	79	153	74	108.1
P--9/3																			
TL	96	58	90	78	86	84	111	74	65	95	78	92	95	74	--	65	111	45	86.7
P	19	26	19	17	28	18	28	15	25	18	21	19	17	19	--	15	28	13	20.8
A	101	124	122	86	178	131	106	102	176	71	70	186	119	124	--	70	186	116	122.8
P+A	120	150	141	103	206	149	134	117	201	89	91	205	136	143	--	91	206	115	143.6

*Min, Max, R, and $\overline{Y}$ are for columns 3 to 12 only.

Table 7

DATA SHEET FOR OPERATOR B

Run	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Min	Max	R	$\bar{Y}$
P--1/7																			
TL	59	72	69	65	60	68	68	68	68	61	64	60	61	63	64	60	69	9	65.1
P	7	8	4	6	10	6	7	5	3	6	9	5	8	3	5	3	10	7	6.1
A	70	66	73	74	66	94	79	82	97	60	58	98	68	57	77	58	97	39	78.1
P+A	77	74	79	80	76	100	86	87	100	66	67	103	76	60	82	66	103	37	84.2
P--2/5																			
TL	64	53	74	61	71	64	58	65	59	61	64	66	62	58	65	53	74	16	64.3
P	23	21	17	17	10	16	13	17	24	21	14	12	12	31	48	10	24	14	16.1
A	102	94	131	99	158	95	104	74	94	114	80	102	132	84	153	74	158	84	105.1
P+A	125	115	148	116	168	111	117	91	118	135	94	114	144	105	201	91	168	77	121.2
P--3/8																			
TL	68	63	69	65	64	67	64	68	65	68	62	65	64	67	65	62	69	7	65.7
P	14	11	7	9	8	8	10	7	7	8	9	8	5	6	8	7	10	3	8.1
A	135	90	110	112	78	105	143	89	141	137	149	98	114	87	107	78	149	71	116.2
P+A	149	101	117	121	86	113	153	96	148	145	158	106	119	93	115	86	158	72	124.3
P--4/2																			
TL	72	73	72	84	95	79	67	75	69	69	65	76	81	--	--	65	95	30	75.1
P	10	7	16	9	8	7	13	9	8	11	5	7	3	--	--	5	16	11	9.3
A	170	146	158	110	138	168	169	173	97	174	177	128	200	--	--	97	177	80	149.2
P+A	180	153	174	119	146	175	182	182	105	185	182	135	203	--	--	105	185	80	158.5
P--5/9																			
TL	65	64	59	57	62	61	59	54	55	67	65	58	62	66	--	54	67	13	59.7
P	14	23	13	13	9	22	10	12	15	14	8	14	13	11	--	8	22	14	13.0
A	102	131	145	109	165	79	92	104	192	182	124	128	134	184	--	79	192	113	132.0
P+A	116	154	158	122	174	101	102	116	207	196	132	142	147	195	--	101	207	106	145.0
P--6/6																			
TL	92	85	82	93	88	89	82	75	76	82	82	84	82	99	81	75	93	18	83.3
P	8	8	7	4	4	12	12	5	5	10	5	5	5	4	17	4	12	8	6.9
A	135	182	113	117	105	108	165	184	87	88	96	82	155	133	86	82	184	102	114.5
P+A	143	190	120	121	109	120	177	189	92	98	101	87	160	137	103	87	189	102	121.4
P--7/1																			
TL	77	90	83	85	96	77	91	92	83	76	74	60	75	75	72	60	96	36	81.7
P	8	14	24	13	6	13	19	10	19	9	10	17	11	8	17	6	24	18	14.0
A	137	79	62	63	57	76	93	77	90	114	91	57	101	67	118	57	114	57	78.0
P+A	145	93	86	76	63	89	112	87	109	123	101	74	112	75	135	63	123	60	92.0
P--8/3																			
TL	100	87	86	85	82	85	85	92	79	81	89	98	87	81	84	81	98	17	86.2
P	8	8	14	10	11	7	4	19	15	9	13	12	17	22	20	4	19	15	11.4
A	112	113	84	129	106	97	168	122	140	153	131	141	143	133	159	84	168	84	127.1
P+A	120	121	98	139	117	104	172	141	155	162	144	153	160	155	179	98	172	74	138.5
P--9/4																			
TL	102	97	106	102	110	122	111	100	114	98	89	107	113	99	93	89	122	33	105.9
P	9	7	8	10	21	34	22	39	25	19	20	20	27	19	19	8	39	31	21.8
A	138	79	178	104	131	139	183	90	79	112	109	170	95	88	83	79	183	104	129.5
P+A	147	86	186	114	152	173	205	129	104	131	129	190	122	107	102	104	205	101	151.3

Table 8

DATA SHEET FOR OPERATOR C

Run	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Min	Max	R	$\bar{Y}$
P--1/8																			
TL	64	62	61	57	64	71	60	61	62	61	59	70	50	64	70	57	71	14	62.6
P	15	18	20	15	21	21	20	20	28	15	17	13	25	10	28	13	28	14	19.0
A	70	82	86	80	106	82	81	88	101	71	101	81	70	82	76	71	106	35	87.7
P+A	85	100	106	95	127	103	101	108	129	86	118	94	95	92	104	86	118	32	106.7
P--2/7																			
TL	61	68	61	65	71	69	60	65	61	64	70	56	56	64	--	56	71	15	64.2
P	15	17	14	18	15	24	19	19	19	22	19	21	27	28	--	14	24	10	19.0
A	102	104	75	137	103	130	104	115	92	100	127	145	105	96	--	75	145	70	112.8
P+A	117	121	89	155	118	154	123	134	111	122	146	166	132	124	--	29	166	77	131.8
P--3/2																			
TL	69	72	65	66	64	58	65	81	81	86	80	78	74	73	76	58	86	28	72.4
P	35	24	21	24	25	24	23	17	14	15	10	15	19	9	15	10	25	15	18.8
A	132	156	126	115	126	144	94	95	131	86	70	138	169	118	106	70	138	68	112.5
P+A	167	180	147	139	151	168	117	112	145	101	80	153	188	127	121	80	168	88	131.3
P--4/9																			
TL	82	78	70	71	67	61	70	76	70	73	70	67	73	68	73	61	76	15	69.5
P	32	25	18	39	29	26	28	23	21	21	38	34	30	38	20	18	39	21	27.7
A	58	70	79	109	124	106	158	82	111	67	90	90	82	109	111	67	158	91	101.6
P+A	90	95	97	148	153	132	186	105	132	88	128	124	112	147	131	88	186	98	129.3
P--5/5																			
TL	68	78	62	73	71	59	67	64	61	70	65	62	63	62	60	71	73	2	65.4
P	23	46	24	25	32	19	20	21	23	19	23	31	22	26	23	19	32	13	23.7
A	145	110	100	133	147	93	115	143	71	140	160	158	128	112	156	51	160	109	124.0
P+A	168	156	124	158	179	112	135	164	74	159	183	189	150	138	179	74	189	115	147.7
P--6/1																			
TL	62	75	92	89	90	85	77	81	105	90	75	117	72	86	--	75	117	42	90.1
P	10	21	10	14	20	7	20	21	32	8	13	11	3	14	--	7	32	25	15.6
A	152	138	173	182	116	147	150	131	100	106	194	122	114	135	--	100	194	94	142.1
P+A	162	159	183	196	136	154	170	152	132	114	207	133	117	149	--	114	207	93	157.7
P--7/4																			
TL	104	93	85	94	92	86	99	84	90	89	100	103	86	95	89	84	100	16	92.2
P	15	8	22	6	7	4	15	12	19	17	9	16	18	8	11	4	22	18	12.7
A	122	17	139	102	130	162	135	140	129	130	151	112	129	121	129	102	162	60	133.0
P+A	137	25	161	108	137	166	150	152	148	147	160	128	147	129	140	108	166	58	145.7
P--8/6																			
TL	75	82	78	86	88	84	77	76	68	78	71	72	75	81	85	68	88	20	77.8
P	21	20	23	23	13	21	16	21	18	18	18	14	15	16	15	13	23	10	18.5
A	113	135	159	99	133	92	118	126	140	142	118	128	95	106	120	92	159	67	125.5
P+A	134	155	182	122	146	113	134	147	158	160	136	142	110	122	135	113	160	47	144.0
P--9/3																			
TL	111	72	95	78	71	115	96	94	82	87	77	104	95	111	104	71	115	44	89.9
P	19	25	19	22	21	18	19	15	20	25	29	28	35	29	26	15	29	14	21.6
A	144	159	152	163	200	164	196	147	142	147	105	92	120	188	186	92	200	108	150.8
P+A	163	184	171	185	221	182	215	162	162	172	134	120	155	217	212	120	221	101	172.4

Table 9

DATA SHEET FOR OPERATOR D

Run	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Min	Max	R	$\overline{Y}$
P--1/1																			
TL	73	68	68	64	64	60	59	66	64	65	60	71	62	65	63	59	71	12	64.1
P	29	20	20	24	20	27	30	34	26	28	24	31	31	22	23	20	34	14	26.4
A	92	111	75	89	84	91	80	85	82	90	89	91	94	85	67	75	91	26	85.6
P+A	121	131	95	113	104	118	110	119	108	118	113	122	125	107	90	95	122	37	112.0
P--2/6																			
TL	60	55	56	55	56	49	52	56	54	61	57	51	50	56	48	49	61	12	54.7
P	24	26	26	38	30	29	41	23	22	39	21	19	30	27	32	19	41	22	28.8
A	88	95	81	96	88	101	106	88	160	106	82	98	84	104	99	81	160	79	100.6
P+A	112	121	107	134	118	130	147	111	182	145	103	117	114	131	131	103	182	79	129.4
P--3/2																			
TL	55	58	54	62	54	53	67	52	56	55	64	60	56	60	--	52	67	15	57.7
P	29	26	22	27	33	27	27	26	29	47	18	16	30	27	--	16	47	31	27.2
A	88	130	97	94	137	82	90	91	145	115	116	135	100	185	--	82	145	63	110.2
P+A	117	151	119	121	170	109	117	117	174	162	134	151	130	212	--	109	170	61	137.4
P--4/9																			
TL	66	55	66	61	68	61	60	69	77	64	62	65	64	60	55	60	77	17	65.3
P	13	29	28	22	14	17	26	18	5	15	15	14	18	17	32	5	26	21	17.4
A	109	84	188	91	121	104	74	104	96	101	109	81	107	101	88	74	188	114	106.7
P+A	122	112	216	113	135	121	100	122	101	116	124	95	125	118	120	95	215	121	124.3
P--5/5																			
TL	60	65	70	59	56	56	59	56	51	55	60	55	66	--	--	51	70	19	57.7
P	38	35	28	31	28	24	20	30	21	32	36	30	25	--	--	20	36	16	28.0
A	156	83	151	155	144	110	108	91	134	126	126	119	99	--	--	91	155	64	126.4
P+A	194	118	179	186	172	134	178	121	155	158	152	149	124	--	--	121	186	65	154.4
P--6/7																			
TL	76	66	78	74	75	67	62	68	76	67	81	79	66	69	61	62	81	19	72.7
P	23	28	18	20	17	33	42	23	13	24	25	21	32	26	27	13	42	29	23.5
A	114	94	98	127	65	142	101	127	85	147	88	129	160	147	104	85	147	62	117.2
P+A	137	122	116	147	102	175	143	150	98	171	113	150	192	173	131	102	175	73	126.5
P--7/3																			
TL	74	92	63	59	68	91	60	63	74	69	66	61	65	--	--	59	91	32	67.4
P	40	28	55	30	37	21	30	34	32	33	30	20	33	--	--	20	55	35	32.9
A	81	128	111	128	90	186	152	155	142	125	139	120	169	--	--	90	186	96	134.8
P+A	121	156	166	158	127	214	182	189	174	158	169	140	202	--	--	127	214	87	167.7
P--8/4																			
TL	75	68	72	70	65	68	71	65	59	65	72	65	61	62	--	59	72	13	67.2
P	18	23	21	29	19	26	20	28	22	20	28	28	9	20	--	20	29	9	24.1
A	116	126	104	80	149	77	101	126	117	130	108	152	106	80	--	80	152	72	114.4
P+A	134	149	125	109	168	103	121	154	139	150	136	180	115	100	--	103	180	77	138.5
P--9/8																			
TL	90	93	95	99	92	90	87	94	84	93	95	93	100	--	--	84	99	15	92.2
P	25	32	31	22	23	23	31	26	24	32	21	22	29	--	--	21	32	11	25.5
A	135	123	123	197	119	111	74	148	156	74	132	99	149	--	--	74	197	123	123.3
P+A	160	155	154	219	142	134	105	174	180	106	153	121	198	--	--	105	219	104	148.8

Table 10

DATA SHEET FOR OPERATOR E

Run	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Min	Max	R	$\bar{Y}$
P--1/3																			
TL	61	57	61	65	62	64	62	60	60	60	63	65	64	65	59	60	65	5	62.2
P	25	25	29	28	26	34	28	35	29	29	32	38	28	26	38	26	38	12	30.8
A	65	90	62	69	66	60	61	60	54	55	145	86	122	91	12	54	145	91	71.8
P+A	90	115	91	97	92	94	89	95	83	84	177	124	150	117	50	83	177	94	102.6
P--2/7																			
TL	70	72	61	64	75	79	68	78	69	76	71	82	82	86	82	61	82	21	72.3
P	11	23	32	39	26	36	32	31	22	40	29	23	24	19	19	22	40	18	31.0
A	105	123	65	80	34	130	82	144	83	72	135	89	101	161	92	65	144	79	96.4
P+A	116	145	97	119	110	166	114	175	105	112	164	112	125	180	111	97	175	78	127.4
P--3/1																			
TL	75	75	68	69	67	59	68	68	67	67	76	75	67	67	69	59	76	17	68.4
P	30	29	33	26	35	36	33	39	33	21	33	33	29	30	24	21	36	15	32.2
A	126	95	137	154	73	158	84	81	117	101	105	99	116	117	118	73	158	85	110.7
P+A	156	124	170	180	108	194	117	120	150	122	136	132	145	147	142	108	194	86	142.9
P--4/6																			
TL	116	67	66	64	64	72	65	61	87	68	78	76	79	--	--	61	87	26	60.1
P	5	20	30	30	16	41	22	28	15	24	22	45	24	--	--	15	45	30	27.3
A	183	103	138	122	108	200	151	165	173	113	134	150	131	--	--	108	200	92	145.4
P+A	188	123	168	152	124	241	173	193	188	137	156	195	155	--	--	124	241	117	172.7
P--5/2																			
TL	75	68	84	74	74	71	72	69	69	73	68	71	70	69	68	68	84	16	72.5
P	23	23	22	22	23	22	36	21	23	32	25	32	26	37	28	21	36	15	25.8
A	96	158	129	94	80	125	87	114	113	134	80	142	82	91	103	80	142	62	109.0
P+A	119	181	151	116	103	147	123	135	146	165	105	174	108	128	131	103	174	71	130.6
P--6/5																			
TL	76	86	91	74	77	90	80	90	80	84	90	85	70	--	--	74	91	17	84.2
P	31	35	13	19	39	40	35	32	22	20	19	21	32	--	--	13	40	27	26.0
A	70	92	74	110	115	137	182	147	157	129	88	90	69	--	--	74	182	108	122.0
P+A	101	117	87	129	154	177	217	179	179	149	107	111	130	--	--	87	217	130	148.9
P--7/9																			
TL	88	85	72	92	101	90	72	67	94	88	67	59	64	67	--	59	101	42	80.2
P	15	9	43	19	8	21	27	28	13	16	35	40	30	32	--	8	43	35	25.0
A	82	132	150	90	85	112	147	131	103	131	147	97	104	82	--	85	150	65	119.3
P+A	97	141	193	109	93	133	174	159	116	147	182	137	134	105	--	93	193	100	144.3
P--8/4																			
TL	97	86	103	95	99	75	91	90	93	89	95	102	87	--	--	89	103	14	93.2
P	33	25	19	22	15	25	18	27	20	29	23	19	22	--	--	18	29	11	21.7
A	141	102	178	113	74	136	127	73	138	110	142	173	192	--	--	73	178	105	126.4
P+A	174	127	197	135	89	161	145	100	158	139	165	192	214	--	--	89	197	108	148.1
P--9/8																			
TL	135	107	116	89	103	84	106	104	95	98	110	109	109	--	--	84	116	32	101.4
P	44	39	31	34	35	90	38	109	42	25	65	41	88	--	--	25	109	84	51.0
A	185	85	182	184	167	165	144	174	182	198	155	159	139	--	--	144	198	54	173.0
P+A	229	124	213	218	202	255	182	303	224	223	220	200	227	--	--	182	303	121	224.0

Table 11

DATA SHEET FOR OPERATOR F

Run	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Min	Max	R	$\bar{Y}$
P--1/9																			
TL	64	64	58	62	62	67	64	71	68	60	65	67	58	63	65	58	71	13	64.4
P	19	17	33	30	26	36	30	29	25	63	34	28	26	26	26	25	63	38	33.4
A	86	110	84	82	81	92	91	84	83	91	87	108	91	77	111	81	108	27	88.3
P+A	105	127	117	112	107	128	121	113	108	154	121	136	117	103	137	107	154	47	121.7
P--2/7																			
TL	65	79	65	69	83	81	69	86	70	67	73	75	78	81	81	65	86	21	73.8
P	30	24	37	29	22	39	16	51	32	36	44	23	28	14	18	16	51	35	32.9
A	127	124	118	135	125	146	129	153	115	124	148	123	109	114	119	115	153	38	131.6
P+A	157	148	155	164	147	185	145	204	147	160	192	146	137	128	137	145	204	59	164.5
P--3/4																			
TL	58	71	72	71	79	69	65	64	62	63	66	63	67	74	70	62	79	47	67.4
P	35	35	43	29	22	30	39	29	34	39	44	37	27	32	36	22	44	22	34.6
A	121	126	124	115	112	172	116	107	109	131	99	168	131	108	164	99	168	69	125.3
P+A	156	161	167	144	134	202	155	136	143	170	143	205	158	140	200	134	205	71	159.9
P--4/8																			
TL	66	70	78	74	77	78	75	72	67	73	69	82	66	69	82	67	82	15	74.5
P	36	34	36	35	31	25	29	29	40	28	32	33	43	31	26	25	40	15	31.8
A	134	148	149	172	160	168	138	128	186	139	141	178	142	145	178	128	186	58	155.9
P+A	170	182	185	207	191	193	167	157	226	167	173	211	185	176	204	157	226	69	187.7
P--5/3																			
TL	62	74	66	65	70	68	67	72	74	76	72	71	69	--	--	65	76	11	70.1
P	44	40	31	31	49	28	29	24	27	12	26	34	30	--	--	12	49	37	29.1
A	164	113	185	156	129	191	124	166	137	149	139	160	141	--	--	124	191	67	153.6
P+A	208	155	216	187	178	219	153	190	164	161	165	194	171	--	--	153	219	66	182.7
P--6/1																			
TL	72	89	68	68	66	81	77	80	67	82	76	82	88	74	69	66	82	16	74.7
P	24	55	29	34	16	25	28	38	31	25	33	24	34	39	28	16	38	22	28.3
A	174	132	174	108	160	159	189	135	138	135	144	127	190	135	149	108	189	81	146.9
P+A	198	187	203	142	176	184	217	173	169	160	177	151	224	174	177	142	217	75	175.2
P--7/5																			
TL	76	72	80	78	86	102	94	89	70	89	81	87	82	71	83	70	102	32	85.6
P	42	26	39	26	23	23	35	26	25	20	18	32	11	26	34	18	39	21	26.7
A	112	158	119	137	117	126	151	132	134	157	149	147	160	168	154	119	157	38	136.9
P+A	154	184	158	163	140	149	186	158	159	177	167	179	171	194	188	140	186	46	163.6
P--8/2																			
TL	83	83	116	97	97	111	124	94	88	104	105	105	91	--	--	88	124	36	104.1
P	9	33	9	25	22	4	10	23	20	15	4	19	18	--	--	4	25	21	15.1
A	126	128	127	166	139	130	156	135	164	135	184	142	184	--	--	127	184	57	147.8
P+A	135	161	136	191	161	134	166	158	184	150	188	161	202	--	--	134	191	57	162.9
P--9/6																			
TL	93	128	115	108	132	121	114	118	134	133	135	114	111	--	--	108	135	27	122.4
P	55	33	47	38	35	50	30	25	35	35	19	30	34	--	--	19	50	31	34.4
A	134	153	200	169	95	105	175	139	198	124	178	192	199	--	--	105	200	95	157.5
P+A	189	186	247	207	130	155	205	164	233	159	197	222	233	--	--	130	247	117	191.9

Table 12

DATA SHEET FOR OPERATOR G

Run	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Min	Max	R	$\bar{Y}$
P--1/8																			
TL	58	58	63	54	61	56	67	58	63	60	69	67	74	58	66	54	69	15	61.8
P	20	23	14	18	19	17	6	22	14	15	9	19	22	20	14	6	22	16	15.3
A	79	73	76	101	81	64	115	97	70	109	62	93	76	102	73	62	115	53	86.8
P+A	99	96	90	119	100	81	121	119	84	124	71	112	98	122	87	81	124	43	102.1
P--2/5																			
TL	55	69	60	60	61	58	61	67	65	64	61	64	66	62	--	58	65	7	62.1
P	25	27	27	28	25	32	25	37	30	26	18	21	16	22	--	18	37	19	26.9
A	88	87	126	122	88	81	102	88	69	79	72	134	76	110	--	69	134	65	96.1
P+A	110	114	153	150	113	113	127	125	99	105	90	155	92	132	--	90	155	65	123.0
P--3/4																			
TL	68	68	72	67	68	67	64	65	73	70	72	70	68	66	70	64	73	9	68.8
P	17	18	16	15	15	16	19	23	19	20	20	24	16	19	19	15	24	9	18.7
A	118	119	116	142	102	167	98	105	125	83	179	75	120	127	144	75	179	104	119.2
P+A	135	137	132	157	117	183	117	128	144	103	199	99	136	146	163	99	199	100	137.9
P--4/7																			
TL	60	61	63	65	61	64	62	60	64	60	67	64	65	69	56	60	67	7	63.0
P	22	24	23	16	31	19	21	19	17	18	16	14	15	16	17	14	31	17	19.4
A	148	113	103	143	173	145	131	73	153	124	95	130	86	149	168	73	173	100	127.5
P+A	170	142	131	159	204	164	152	92	170	142	111	144	102	165	185	92	204	112	146.9
P--5/2																			
TL	78	94	85	83	74	81	76	77	84	82	91	78	81	--	--	76	91	15	81.1
P	28	4	12	33	25	15	23	28	34	10	14	23	23	--	--	10	34	24	21.7
A	115	144	120	118	107	120	163	103	127	173	90	101	161	--	--	90	173	83	122.2
P+A	143	148	132	151	132	135	186	131	161	183	104	124	184	--	--	104	186	82	143.9
P--6/9																			
TL	69	65	65	68	60	62	75	58	65	72	74	83	61	--	--	58	83	25	68.2
P	24	13	16	17	20	15	18	15	28	12	33	23	22	--	--	12	33	21	17.9
A	108	113	120	92	91	123	88	125	130	125	120	84	108	--	--	84	130	46	110.3
P+A	132	126	136	111	111	143	106	140	158	137	153	107	130	--	--	106	158	52	130.2
P--7/6																			
TL	97	75	88	76	75	82	74	68	75	74	70	74	67	73	--	68	88	20	75.6
P	37	18	47	29	28	23	38	40	33	42	35	43	62	32	--	23	47	24	35.8
A	147	122	171	170	160	119	127	137	119	116	113	133	162	86	--	113	171	58	136.5
P+A	184	140	218	199	188	142	165	177	152	158	148	176	224	118	--	142	218	76	172.3
P--8/1																			
TL	99	79	84	98	102	100	82	96	98	91	83	76	96	93	--	76	102	26	91.0
P	14	28	19	9	7	22	16	18	7	8	24	30	8	9	--	7	30	23	16.0
A	133	98	146	180	110	107	161	135	183	117	170	162	177	154	--	107	183	76	147.1
P+A	147	126	165	189	117	129	177	153	190	125	194	192	185	163	--	117	194	77	163.1
P--9/3																			
TL	113	118	119	108	122	128	132	125	111	107	112	101	95	--	--	101	132	31	116.4
P	44	23	13	26	22	12	16	8	29	22	22	26	22	--	--	8	29	21	19.6
A	182	182	159	69	74	68	187	111	105	111	76	119	172	--	--	69	187	118	107.9
P+A	226	205	172	95	96	80	203	119	134	133	98	145	194	--	--	95	203	108	127.5

Table 13

DATA SHEET FOR OPERATOR H

Run	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Min	Max	R	$\bar{Y}$
P--1/7																			
TL	58	57	54	59	57	61	57	59	61	56	58	63	64	62	--	54	63	9	58.5
P	19	21	13	16	15	14	21	18	28	22	23	12	14	10	--	12	28	16	18.2
A	77	49	80	44	49	89	83	52	85	54	79	80	62	70	--	44	89	45	69.5
P+A	96	70	93	60	64	103	104	70	113	76	102	92	76	80	--	60	113	53	87.7
P--2/5																			
TL	65	59	67	65	61	63	58	57	58	58	64	62	60	63	--	57	67	10	61.3
P	20	22	21	17	25	29	21	18	21	19	18	16	15	17	--	16	29	13	20.5
A	59	105	78	61	52	51	54	84	58	52	65	64	53	102	--	51	84	33	61.9
P+A	79	127	99	78	77	80	75	102	79	71	83	80	68	119	--	75	102	27	82.4
P--3/8																			
TL	64	57	55	59	59	57	59	58	57	60	60	58	63	--	--	55	60	5	58.2
P	15	14	15	9	14	14	12	21	20	12	9	12	11	--	--	9	21	11	13.8
A	119	53	52	94	60	53	62	59	118	52	49	68	68	--	--	49	118	69	66.7
P+A	134	67	67	103	74	67	74	80	138	64	58	80	79	--	--	58	138	80	80.5
P--4/6																			
TL	58	57	59	60	55	69	57	62	57	59	59	64	62	--	--	57	69	12	60.1
P	11	21	23	17	28	22	[illegible]	[illegible]	15	[illegible]	22	22	28	--	--	16	28	12	21.0
A	106	80	112	56	89	92	120	123	57	52	77	69	59	--	--	52	123	71	84.7
P+A	117	101	135	73	117	114	140	143	73	72	99	91	87	--	--	72	143	71	105.7
P--5/4																			
TL	56	54	57	58	55	54	62	59	64	54	52	60	61	53	--	52	64	12	57.5
P	28	28	24	25	23	28	25	17	17	27	29	27	28	29	--	17	28	11	24.4
A	91	108	149	157	89	129	102	132	158	74	108	123	73	106	--	74	158	84	122.1
P+A	119	136	173	182	112	157	127	149	177	101	137	150	101	135	--	101	182	82	146.5
P--6/3																			
TL	58	62	62	58	68	65	52	55	56	58	54	55	50	65	58	52	68	16	58.3
P	22	28	21	21	10	19	22	22	19	22	20	18	25	19	20	10	22	12	19.4
A	105	166	127	115	145	94	179	92	113	137	121	83	97	85	95	83	179	96	122.6
P+A	127	194	168	136	155	113	201	114	130	159	141	101	120	104	115	101	201	100	142.0
P-7/2																			
TL	76	69	65	75	71	64	57	64	62	61	59	60	59	62	62	57	75	18	64.8
P	37	26	15	18	19	15	17	13	19	16	25	18	14	11	14	13	25	12	17.5
A	113	123	106	103	103	104	93	89	95	77	107	97	77	140	97	77	107	30	97.4
P+A	150	149	121	121	122	119	110	102	114	93	132	115	91	151	111	93	132	39	114.9
P--8/1																			
TL	73	74	70	74	71	75	74	72	72	76	72	74	63	71	64	70	76	6	73.0
P	19	15	15	15	12	19	14	14	12	11	13	15	15	12	20	11	19	8	14.0
A	145	104	83	104	108	119	85	80	116	75	105	70	67	116	97	70	119	49	94.5
P+A	164	119	98	119	120	138	99	94	128	86	118	85	82	128	122	85	138	53	108.5
P--9/9																			
TL	79	79	68	72	69	75	80	80	78	86	84	72	88	79	67	68	86	18	77.4
P	13	16	15	22	18	18	18	20	28	15	14	18	22	22	16	14	28	14	18.6
A	144	167	162	84	162	124	147	112	112	160	162	142	138	109	136	84	162	78	136.7
P+A	157	183	177	106	180	142	165	132	140	175	176	160	160	131	152	106	180	74	155.3

Table 14

DATA SHEET FOR OPERATOR I

Run	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Min	Max	R	$\bar{Y}$
P--1/9																			
TL	55	55	55	54	53	52	56	53	57	53	51	53	49	53	51	51	57	6	53.7
P	19	15	22	15	19	18	21	17	21	19	21	22	28	22	21	17	22	5	19.5
A	64	69	77	72	56	74	64	58	61	62	74	61	55	81	68	56	77	21	65.9
P+A	83	84	99	87	75	92	85	75	82	81	95	83	83	103	89	75	99	24	85.4
P--2/7																			
TL	57	60	59	65	53	54	55	50	54	57	56	49	50	--	--	49	65	16	55.2
P	20	25	25	19	30	23	20	22	21	23	21	26	19	--	--	19	30	11	23.0
A	77	94	98	99	77	96	106	90	121	117	101	93	82	--	--	77	121	44	99.8
P+A	97	119	123	118	107	119	126	112	142	140	122	119	101	--	--	107	142	35	122.8
P--3/6																			
TL	53	52	50	54	55	48	50	52	48	51	52	53	54	54	60	48	55	7	51.3
P	23	22	22	19	25	22	26	24	22	22	28	19	22	28	23	19	28	9	22.9
A	92	86	92	94	74	89	107	86	110	79	91	81	140	145	78	74	110	36	90.3
P+A	115	108	114	113	99	111	133	110	132	101	119	100	162	173	101	99	133	34	113.2
P--4/4																			
TL	61	65	55	54	54	56	57	60	55	55	57	63	54	57	--	54	63	9	56.0
P	29	21	21	25	30	26	28	23	28	35	30	29	26	29	--	21	36	15	28.1
A	141	143	89	125	104	125	132	159	158	180	167	111	165	105	--	89	180	91	134.5
P+A	170	164	110	150	134	151	160	182	186	215	198	140	191	134	--	110	215	105	[illegible]
P--5/8																			
TL	60	56	58	60	61	70	76	64	57	68	69	61	63	[illegible]	60	57	76	19	[illegible]
P	15	11	12	12	16	6	14	10	12	13	8	9	12	12	8	6	14	8	11.2
A	117	76	114	111	95	96	90	100	87	74	99	112	98	87	84	74	114	40	97.8
P+A	132	107	126	123	111	102	104	110	99	87	107	121	110	99	92	87	126	39	109.0
P--6/1																			
TL	84	89	80	76	72	80	80	90	89	93	82	85	110	91	77	72	93	21	82.7
P	28	16	19	19	18	22	15	18	9	8	15	22	19	16	26	8	22	14	16.5
A	111	109	87	112	91	143	96	173	94	171	114	113	102	75	135	91	171	80	[illegible]
P+A	139	125	106	131	109	165	111	191	103	179	129	135	121	91	161	103	179	76	[illegible]
P--7/2																			
TL	95	68	71	75	72	87	71	64	64	65	74	61	66	--	--	64	87	23	70.4
P	19	25	11	13	11	6	15	19	16	22	13	19	15	--	--	6	22	16	14.5
A	174	172	113	139	196	127	140	127	132	135	98	116	150	--	--	98	196	96	132.3
P+A	193	197	124	152	207	133	155	146	148	157	111	135	165	--	--	111	207	96	146.3
P--8/5																			
TL	63	68	55	59	55	82	52	54	52	55	60	57	57	53	55	52	82	30	58.1
P	22	23	29	25	38	33	22	23	17	23	20	16	21	20	21	16	38	22	24.6
A	134	106	128	134	108	115	105	135	137	103	95	64	109	112	111	84	137	53	114.4
P+A	156	129	157	159	146	148	127	158	154	126	115	100	130	132	132	100	159	59	139.0
P--9/3																			
TL	121	90	102	135	106	103	106	104	101	122	128	103	181	--	--	101	135	34	111.0
P	13	44	36	18	37	44	29	34	39	29	26	29	12	--	--	18	44	26	32.1
A	118	79	101	146	130	119	194	158	171	108	179	174	64	--	--	101	194	93	148.0
P+A	131	123	137	164	167	163	223	192	210	137	205	203	76	--	--	137	223	86	180.1

Table 15

DATA SHEET FOR OPERATOR J

Run	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Min	Max	R	$\bar{Y}$
P--1/7																			
TL	44	44	47	40	54	41	42	41	40	39	42	40	42	41	41	39	54	15	42.5
P	16	15	18	19	10	18	22	12	16	18	16	15	15	15	14	10	22	12	15.4
A	42	49	36	27	58	49	48	38	38	30	38	32	61	38	30	27	58	31	39.4
P+A	58	64	54	46	68	67	70	50	54	48	54	47	76	53	44	46	70	24	55.8
P--2/6																			
TL	52	51	52	47	48	47	46	46	46	45	49	47	44	45	--	45	52	7	47.3
P	23	16	30	19	23	17	19	21	19	21	19	19	23	26	--	19	30	11	20.7
A	90	49	90	61	54	53	83	49	83	58	63	62	71	52	--	53	90	37	65.6
P+A	113	65	120	80	77	70	102	70	102	79	82	81	94	78	--	70	120	50	86.3
P--3/4																			
TL	52	52	50	49	49	46	56	50	46	52	52	52	52	51	54	46	56	10	50.2
P	25	24	22	14	21	15	18	21	23	26	21	18	17	18	12	15	26	11	20.0
A	45	87	71	45	36	45	83	97	83	81	45	43	48	92	83	36	97	61	62.7
P+A	70	111	93	60	57	60	101	118	106	107	66	61	65	110	95	57	118	61	[illegible]
P--4/1																			
TL	58	49	58	47	49	49	45	44	46	51	50	52	45	49	--	44	58	14	49.1
P	28	19	22	22	25	26	23	20	25	17	28	28	18	26	--	17	78	11	25.6
A	142	147	142	120	112	81	83	124	124	103	149	72	87	10	--	72	149	77	111.0
P+A	170	166	164	142	137	107	106	144	149	120	197	100	105	36	--	100	177	77	134.6
P--5/8																			
TL	46	46	49	50	48	49	61	53	52	52	50	51	49	--	--	48	61	13	51.5
P	20	17	19	25	19	22	8	19	25	20	28	22	20	--	--	8	28	20	20.7
A	103	104	145	140	95	125	125	97	102	118	105	120	108	--	--	95	145	50	117.2
P+A	123	121	164	165	114	147	133	116	127	138	133	142	128	--	--	114	165	51	137.9
P--6/5																			
TL	50	64	57	56	57	54	60	68	50	59	58	58	68	--	--	54	69	14	57.7
P	46	25	79	23	26	22	26	45	29	37	30	27	77	--	--	22	45	23	29.4
A	76	155	79	84	88	96	150	82	79	72	80	111	108	--	--	72	150	82	92.1
P+A	122	180	108	107	114	118	176	127	108	109	110	138	185	--	--	107	176	69	121.5
P--7/9																			
TL	65	63	57	61	59	67	72	59	58	60	57	58	55	--	--	57	72	15	60.8
P	22	19	23	26	18	22	23	20	25	32	25	22	23	--	--	18	32	14	23.6
A	83	96	109	93	70	86	64	87	69	88	110	75	95	--	--	64	110	44	85.1
P+A	105	115	132	119	88	108	87	107	94	120	135	97	118	--	--	87	135	48	108.7
P--8/3																			
TL	83	72	85	61	57	64	64	88	68	77	74	62	68	60	62	57	88	31	70.0
P	12	22	6	18	18	17	18	17	19	9	19	16	18	21	19	6	19	13	15.7
A	125	101	112	94	113	106	77	53	85	115	49	64	104	105	95	49	115	66	86.8
P+A	137	123	118	112	131	123	95	70	104	124	68	80	122	126	114	68	131	64	102.5
P--9/2																			
TL	153	159	181	173	192	168	139	154	155	114	126	161	153	154	156	114	192	78	156.3
P	83	10	92	36	20	6	10	54	23	54	18	39	66	25	7	6	92	86	35.2
A	142	119	122	182	93	83	180	92	148	68	96	147	126	125	123	68	132	114	121.1
P+A	225	129	214	218	113	89	190	146	171	122	114	186	192	150	130	113	218	105	156.3

Table 16

DATA SHEET FOR OPERATOR K

Run	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Min	Max	R	$\bar{Y}$
P--1/9																			
TL	53	52	54	56	53	53	49	49	57	65	49	52	54	58	57	49	65	16	53.7
P	27	20	18	18	23	20	25	15	18	23	23	18	18	16	16	15	25	10	20.1
A	68	68	73	69	70	65	61	72	64	61	58	65	64	62	68	58	73	15	65.8
P+A	95	88	91	87	93	85	86	87	82	84	81	83	82	78	84	81	93	12	85.9
P--2/4																			
TL	68	73	61	65	70	68	68	75	67	107	65	65	68	65	66	61	107	46	71.1
P	12	19	19	27	35	22	14	12	12	12	13	14	11	15	17	12	35	23	18.0
A	93	102	97	84	111	76	93	81	88	104	104	88	88	93	96	76	111	35	92.6
P+A	105	121	116	111	146	98	107	93	100	116	117	102	99	108	113	98	146	48	110.6
P--3/7																			
TL	62	65	62	68	55	59	57	51	64	72	72	64	70	--	--	51	72	21	62.4
P	19	16	37	49	38	20	20	28	17	17	18	13	22	--	--	13	49	36	25.7
A	115	110	117	135	133	92	79	57	104	121	90	85	50	--	--	57	135	78	101.3
P+A	134	126	154	184	171	112	99	85	121	138	108	98	72	--	--	85	184	99	127.0
P--4/6																			
TL	65	73	80	67	72	70	76	57	85	78	67	63	61	58	--	63	85	22	71.5
P	24	33	16	36	19	22	23	39	13	26	22	16	21	29	--	13	36	23	23.2
A	175	114	130	147	93	119	114	105	99	131	153	119	106	77	--	93	153	60	121.0
P+A	199	147	146	183	112	141	137	144	112	157	175	135	127	106	--	112	183	71	144.2
P--5/3																			
TL	69	64	62	72	70	78	67	73	68	81	82	81	77	72	--	62	82	20	73.4
P	26	13	23	8	14	6	22	9	10	5	6	5	9	5	--	5	23	18	10.8
A	139	119	117	110	132	136	114	147	84	88	107	104	109	136	--	84	136	52	113.9
P+A	165	132	140	118	146	142	136	156	94	93	113	109	118	141	--	93	146	53	124.7
P--6/8																			
TL	69	75	82	75	61	65	80	81	76	63	92	78	71	71	--	61	92	31	75.3
P	24	20	27	9	17	40	32	43	32	49	23	36	12	26	--	9	49	40	30.8
A	123	119	69	117	114	102	115	95	88	110	90	92	114	105	--	69	117	48	99.2
P+A	147	139	96	126	131	142	147	138	120	159	113	128	126	131	--	96	159	63	130.0
P--7/1																			
TL	83	76	76	89	100	86	78	86	92	91	90	93	89	76	--	76	100	24	88.1
P	53	29	47	18	12	28	23	16	14	17	28	9	26	47	--	9	28	19	21.2
A	118	92	81	117	68	109	182	104	154	95	119	86	119	116	--	68	182	114	111.5
P+A	171	121	128	135	80	137	205	120	168	112	147	95	145	163	--	80	205	125	132.7
P--8/2																			
TL	76	77	85	73	74	75	81	82	79	70	79	86	76	80	--	70	86	16	78.4
P	15	17	8	29	29	17	9	16	18	29	29	16	22	17	--	8	29	21	20.0
A	105	99	102	111	147	159	71	110	111	83	126	89	97	107	--	71	159	88	110.9
P+A	120	116	110	140	176	176	80	126	129	112	155	105	119	124	--	80	176	96	130.9
P--9/5																			
TL	146	168	143	165	144	152	117	143	130	152	144	139	133	159	--	130	165	35	142.9
P	24	51	25	23	15	34	19	8	32	9	18	9	12	19	--	8	34	26	19.2
A	143	177	197	158	127	133	175	173	146	182	172	183	170	199	--	127	197	70	164.6
P+A	167	228	222	181	142	167	194	181	178	191	190	192	182	218	--	142	222	80	183.8

Table 17

DATA SHEET FOR OPERATOR L

Run	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Min	Max	R	$\overline{Y}$
P--1/5																			
TL	54	48	54	53	52	56	54	49	46	49	43	46	49	45	50	43	56	13	50.2
P	15	22	22	14	25	18	23	22	30	42	30	22	18	33	13	14	42	28	24.8
A	82	116	93	122	105	73	86	85	58	80	51	65	69	119	54	51	122	71	81.8
P+A	97	138	115	136	130	91	109	107	88	122	81	87	87	152	67	81	136	55	106.6
P--2/3																			
TL	53	60	45	61	72	60	57	55	63	53	54	50	51	54	46	45	72	27	57.0
P	19	18	34	35	48	40	20	22	19	17	32	16	17	16	17	16	48	32	28.3
A	85	78	77	66	98	96	79	107	69	63	75	68	58	56	59	63	107	44	79.8
P+A	104	96	111	101	146	136	99	129	88	80	107	84	75	72	76	80	146	66	108.1
P--3/9																			
TL	49	72	66	74	63	63	61	66	54	68	61	49	50	57	76	54	74	20	62.5
P	38	7	9	11	33	11	23	15	13	20	18	45	39	18	19	9	45	36	19.8
A	64	88	94	88	94	99	81	81	128	83	77	58	72	116	63	77	128	51	88.3
P+A	102	95	103	99	127	110	104	96	141	103	95	103	111	134	82	95	141	46	108.1
P--4/1																			
TL	72	77	63	84	68	68	64	72	72	72	68	72	69	74	67	63	84	21	70.3
P	23	23	25	35	26	15	31	17	19	18	8	47	44	28	16	8	47	39	24.1
A	79	106	69	89	116	93	79	96	114	86	124	86	126	68	90	69	124	65	95.2
P+A	102	129	94	124	142	108	110	113	133	104	132	133	170	96	106	94	142	48	119.3
P--5/7																			
TL	56	51	49	48	55	52	51	51	54	48	54	55	50	54	48	48	55	7	51.7
P	12	20	23	16	23	25	30	29	27	45	26	29	34	25	30	16	45	29	27.3
A	118	70	62	131	83	95	103	60	105	113	87	89	96	96	97	60	131	71	92.8
P+A	130	90	85	147	106	120	133	89	122	158	113	118	130	121	127	85	158	73	120.1
P--6/8																			
TL	62	71	81	63	67	70	74	69	72	61	73	68	61	79	73	61	81	21	69.8
P	22	61	26	49	33	25	37	41	19	24	16	13	19	13	17	13	49	36	28.3
A	116	66	84	69	122	75	74	111	78	117	114	124	133	99	139	69	124	55	96.8
P+A	138	127	110	118	155	100	111	152	97	141	130	137	152	112	156	97	155	58	125.1
P--7/2																			
TL	88	98	100	87	79	77	80	101	93	81	95	91	102	102	108	77	101	24	88.4
P	19	19	13	33	10	10	23	17	24	17	20	21	24	62	16	10	33	23	18.8
A	44	75	85	67	103	74	49	128	115	79	60	126	62	69	76	60	128	68	88.6
P+A	63	94	98	100	113	84	72	145	139	96	80	147	86	81	92	72	147	75	107.4
P--8/4																			
TL	85	67	88	73	80	73	71	80	83	76	77	76	77	79	72	71	88	17	77.7
P	13	9	5	18	7	15	42	14	11	13	16	14	22	17	10	5	42	37	15.5
A	94	128	74	68	119	109	85	72	71	90	74	71	68	67	96	68	119	51	83.3
P+A	107	137	79	86	126	124	127	86	82	103	90	85	90	84	106	82	127	45	98.8
P--9/6																			
TL	123	126	132	114	141	89	133	130	123	112	133	109	100	101	118	109	133	24	121.6
P	6	8	12	14	17	20	15	8	7	27	19	22	25	16	25	7	27	20	16.1
A	156	188	194	183	138	188	74	158	193	159	192	152	178	121	157	74	194	120	163.1
P+A	162	196	206	197	155	208	89	166	200	186	211	174	203	137	182	89	211	122	179.2

Table 18

DATA SHEET FOR OPERATOR M

Run	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Min	Max	R	$\overline{Y}$
P--1/1																			
TL.	65	65	68	75	73	75	33	77	73	74	72	66	67	64	67	72	77	5	73.6
P	22	28	25	29	25	29	33	24	20	31	32	19	23	26	26	20	33	13	26.7
A	68	47	59	73	65	75	57	59	72	65	59	75	71	50	58	57	73	16	65.9
P+A	90	75	84	102	90	104	90	83	92	96	91	94	94	76	84	83	104	21	92.6
P--2/9																			
TL	61	70	73	69	69	64	64	61	64	64	69	60	65	76	--	60	73	13	65.7
P	24	28	26	29	28	24	26	31	32	29	32	31	28	22	--	24	32	8	28.8
A	64	84	76	76	90	68	81	72	72	82	68	71	73	74	--	68	90	22	75.6
P+A	88	112	102	105	118	92	107	103	104	111	100	102	101	96	--	92	118	26	104.4
P--3/2																			
TL	72	70	75	77	77	73	77	92	82	75	72	75	73	78	--	72	92	20	77.5
P	27	25	24	37	31	30	23	34	37	19	23	24	28	33	--	19	37	18	28.2
A	64	74	115	101	120	100	93	104	105	123	76	90	76	85	--	76	123	47	102.7
P+A	91	99	139	138	151	130	116	138	142	142	99	114	104	118	--	99	151	52	130.9
P--4/6																			
TL	62	63	58	60	60	66	67	74	65	69	64	64	60	59	--	58	69	11	64.7
P	29	45	36	37	37	34	41	36	30	36	34	38	37	36	--	30	41	11	35.9
A	110	94	91	51	108	142	68	142	121	86	104	109	85	85	--	51	142	91	102.2
P+A	139	139	127	88	145	176	109	178	151	122	138	147	122	121	--	88	178	90	138.1
P--5/7																			
TL	61	64	72	69	69	65	67	65	68	61	62	62	68	62	67	61	72	11	66.0
P	29	29	41	33	22	28	31	27	27	14	41	27	25	34	24	14	33	19	29.1
A	84	107	97	102	135	117	134	140	128	90	103	94	80	145	124	90	140	50	114.0
P+A	133	136	138	135	157	145	165	167	155	104	144	121	105	179	148	104	167	63	143.1
P--6/3																			
TL	77	87	86	80	97	87	86	79	87	76	69	77	56	70	--	69	97	9	82.4
P	44	31	30	36	51	36	36	35	47	35	30	37	40	35	--	30	47	17	37.3
A	131	111	140	142	129	159	174	99	137	127	104	85	152	105	--	85	174	91	129.6
P+A	175	142	170	178	180	195	210	134	184	162	134	122	192	140	--	122	210	88	166.9
P--7/5																			
TL	68	71	61	70	64	68	75	82	67	70	69	73	64	71	72	64	82	18	69.9
P	33	24	39	22	26	28	25	9	41	22	28	28	25	20	29	9	39	30	26.8
A	118	132	97	114	84	125	86	129	135	124	133	139	154	135	114	84	139	55	116.6
P+A	151	156	136	136	110	153	111	138	176	146	161	167	179	155	143	110	176	66	143.4
P--8/4																			
TL	71	74	72	81	65	68	71	65	68	68	64	67	33	69	--	64	81	17	68.9
P	28	18	27	24	44	26	27	23	28	29	32	31	30	37	--	23	44	19	29.1
A	103	82	109	127	119	109	102	113	145	111	135	123	108	88	--	102	145	43	119.3
P+A	131	100	136	151	163	135	129	136	173	140	167	154	138	125	--	129	173	44	148.4
P--9/8																			
TL	114	107	118	117	123	126	130	136	108	108	106	106	103	118	105	106	136	30	117.8
P	44	44	49	29	54	50	39	41	36	58	36	42	29	35	41	29	58	29	43.4
A	150	84	171	139	79	168	119	98	192	163	200	185	195	96	171	79	200	121	151.4
P+A	194	128	220	168	133	218	158	139	228	221	236	227	224	131	212	133	236	103	194.8

Table 19

DATA SHEET FOR OPERATOR N

Run	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Min	Max	R	$\bar{Y}$
P--1/6																			
TL	52	54	53	53	55	54	51	52	53	55	54	50	67	57	60	50	55	5	52.8
P	13	20	11	17	11	12	13	14	13	14	15	17	8	10	15	11	17	6	13.7
A	63	50	84	62	46	59	59	50	74	54	60	63	96	74	49	46	84	38	61.1
P+A	76	70	95	79	57	71	72	64	87	68	75	80	104	84	64	57	95	38	74.8
P--2/1																			
TL	47	46	44	48	47	53	49	51	52	53	50	47	49	55	45	44	53	9	49.4
P	20	15	18	29	25	13	22	22	18	23	17	22	21	24	25	13	29	16	20.9
A	120	123	104	147	162	98	99	75	110	111	109	83	93	110	121	75	162	87	109.8
P+A	140	138	122	176	187	[illegible]	121	97	128	134	126	105	114	134	146	97	187	90	130.7
P--3/3																			
TL	54	51	51	49	51	48	50	58	58	57	53	54	56	--	--	48	58	10	52.9
P	13	18	22	22	19	23	21	19	29	22	24	19	13	--	--	19	29	10	22.0
A	115	92	79	77	113	143	111	126	130	39	84	113	98	--	--	77	143	66	106.5
P+A	128	110	101	99	132	166	132	145	159	111	108	132	111	--	--	99	166	67	128.5
P--4/2																			
TL	45	45	46	43	43	43	42	43	50	49	40	44	42	42	41	40	50	10	44.3
P	26	20	24	36	32	27	31	28	28	30	34	34	36	29	26	24	36	12	30.4
A	66	88	79	69	64	77	102	91	79	111	98	62	105	68	97	62	111	49	83.2
P+A	92	108	103	105	96	104	133	119	107	[illegible]	[illegible]	96	141	97	123	96	[illegible]	48	113.6
P--5/7																			
TL	53	53	59	54	64	57	61	74	57	52	55	54	54	53	--	52	64	12	58.7
P	20	24	14	22	17	18	16	21	19	20	22	29	27	23	--	14	29	15	19.8
A	88	23	32	89	86	77	78	68	82	68	84	65	96	62	--	65	89	34	77.9
P+A	108	47	96	111	103	95	94	89	101	88	106	94	123	85	--	88	111	23	97.7
P--6/9																			
TL	43	56	54	53	52	54	52	44	64	52	49	50	54	50	49	44	64	20	52.4
P	26	27	28	22	22	20	24	23	23	19	22	26	23	25	25	19	28	9	23.9
A	86	93	100	109	104	97	86	97	120	128	106	105	39	122	90	86	128	42	105.2
P+A	112	120	128	131	126	119	110	120	143	147	128	131	112	147	115	110	147	37	128.3
P--7/8																			
TL	65	71	75	70	69	92	90	89	76	79	95	82	75	68	65	70	99	29	83.7
P	38	50	23	36	26	16	30	39	26	24	17	18	26	38	38	16	39	23	25.5
A	100	94	131	75	112	93	138	107	117	96	101	76	79	86	115	75	138	63	104.6
P+A	138	144	154	[illegible]	138	109	168	146	143	120	118	94	105	124	153	94	168	74	130.1
P--8/4																			
TL	96	86	76	80	71	76	72	70	64	71	59	58	64	63	--	58	80	22	69.7
P	19	12	18	4	15	20	7	17	23	16	17	23	13	29	--	4	23	19	16.0
A	116	73	112	167	64	84	84	112	111	67	67	90	141	141	--	64	167	103	94.8
P+A	135	85	130	171	79	94	91	129	134	83	84	113	154	170	--	83	171	88	110.8
P--9/5																			
TL	97	71	106	117	157	126	107	107	105	115	107	92	97	--	--	92	157	65	114.0
P	34	50	30	22	43	33	30	33	34	30	30	38	40	--	--	22	43	21	32.3
A	59	125	139	167	155	145	73	144	154	87	128	170	148	--	--	73	170	97	138.2
P+A	93	175	169	189	209	178	103	177	198	117	158	208	188	--	--	103	208	105	170.5

APPENDIX D

STATISTICAL ANALYSIS

I--Computation of Analysis of Variance

A mixed factorial design without replication based on the mean values of times was employed for the analysis of variance. The factor of Operators was a random effect, whereas the factor of Profiles was considered to be a fixed effect. The sample problem outlined below was based on the Transport Loaded (TL) therblig summarized in Table 1.

1. Computation of Average Range ($\bar{R}..$)

$$\bar{R}.. = \frac{\sum_i \sum_j R_{ij}}{op}$$

where $\bar{R}.. =$ Average range

$R_{ij} =$ Range for a particular cell

$o =$ number of operators

$p =$ number of profiles

Example: $\bar{R}.. = \frac{1931}{(14)(8)} = 17.24$

2. Computation of Correction Term (C.T.)

$$C.T. = \frac{T..^2}{N}$$

where $T..$ = total of all values for the o x p cells

N = o x p = total number of cells

Example: $C.T. = \frac{(7385.1)^2}{(14)(8)} = 486{,}961.63$

3. Computation of sum of squares due to Profiles (P)

$$P = \frac{\sum_{j} T._{j}^{2}}{o} - C.T.$$

where $T._{j}$ = sum for each of the o rows

Example: $P = \frac{6,891,862.05}{14} - C.T.$

$= 492,275.80 - C.T. = 5314.23$

4. Computation of sum of squares due to Operators (O)

$$O = \frac{\sum_{i} T_{i.}^{2}}{p} - C.T.$$

where $T_{i.}$ = sum for each of the p columns

$P = \frac{3,962,498.79}{8} - C.T.$

$= 495,312.35 - C.T. = 8350.72$

5. Computation of sum of squares due to Interaction (O x P) and Error

$$OxP(Error) = \sum_{i} \sum_{j} Y_{ij}^{2} - P - O - C.T.$$

where Y_{ij} = value of mean in each cell

Example: OxP = 504921.41 - P - O - C.T.

= 4294.83

6. Computation of the Total sum of squares

T = P + O + OxP

= 17959.78

7. Computation of degrees of freedom:

Source of Variation	Formula	Degrees of Freedom
T	N - 1	111
O	o - 1	7
P	p - 1	13
OxP(Error)	(o - 1)(p - 1)	91

8. Computation of mean squares for the sources of variation

$$\text{Mean square (MS)} = \frac{\text{Sum of squares (SS)}}{\text{Degrees of freedom (d.f.)}}$$

Example: $$MS\ (O) = \frac{8350.72}{13} = 642.36$$

9. Computation of the F_c values for the variation due to Profiles

The F_c values for the Profile source of variation were obtained by determination of the ratio between the means squares for the Profile effect and for the Interaction-plus-Error effect

Example: $$F_c = \frac{759.18}{47.20} = 16.08$$

10. Comparison of computed F_c values and tabulated F values

F values for particular levels of significance were obtained from Dixon and Massey[6] by entering the appropriate table with degrees of freedom for the profile and interaction sources of variation.

$F_{(.010)}\ 7, 91 = 2.83$

$F_{(.025)}\ 7, 91 = 2.43$

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

11. Estimate of the mean square due to Error

An estimate of σ_e^2 was obtained from the formula:

$\sigma_e^2 \doteq \left(\frac{\bar{R}}{d_2}\right)^2$ where d_2 was the factor for the central line of the control chart for ranges.

Example: $\sigma_e^2 \doteq \left(\frac{17.24}{3.078}\right)^2 = 31.36$

Table 20

VERIFICATION OF HOMOGENEITY OF VARIANCES

3-sigma control limits for Ranges:

$$\left.\begin{array}{l}\text{Upper limit} = D_4\bar{R} \\ \text{Central line} = \bar{R} \\ \text{Lower limit} = D_3\bar{R}\end{array}\right\} \text{for sample of size } n = 10 \quad \left\{\begin{array}{l} D_4 = 1.777 \\ D_3 = 0.223 \end{array}\right.$$

	Profiles 1 - 9		Profiles 1 - 8	
Therblig	$\bar{R}$	Control Limits	$\bar{R}$	Control Limits
TL	19.4	UCL - 34.5 LCL - 4.3	17.24	UCL - 30.6 LCL - 3.8
P	19.5	UCL - 34.6 LCL - 4.3	18.10	UCL - 32.2 LCL - 4.0
A	69.0	UCL -122.8 LCL - 15.4	65.11	UCL -115.7 LCL - 14.5
P+A	71.3	UCL -126.5 LCL - 15.9	67.30	UCL -119.6 LCL - 15.0

Table 21

ANALYSIS OF VARIANCE TABLES

Transport Loaded (TL) Therblig

Source of Variation	df	SS	MS	F_c
Profile	7	5314.23	759.18	16.08**
Operator	13	8350.72	642.36	
O x P (Error)	91	4294.83	47.20	
Total	111	17959.78		

$\sigma_e^2 \doteq 31.36$

Position (P) Therblig

Source of Variation	df	SS	MS	F_c
Profile	7	391.97	56.00	2.48†
Operator	13	2760.78	212.37	
O x P (Error)	91	2052.75	22.56	
Total	111	5205.50		

$\sigma_e^2 \doteq 34.57$

Assemble (A) Therblig

Source of Variation	df	SS	MS	F_c
Profile	7	23862.99	3409.00	18.92**
Operator	13	23066.26	1774.33	
O x P (Error)	91	16398.41	180.20	
Total	111	63327.66		

$\sigma_e^2 \doteq 447.32$

Position-and-Assemble (P-A) Therblig

Source of Variation	df	SS	MS	F_c
Profile	7	25502.99	3643.28	17.20**
Operator	13	30370.84	2336.22	
O x P (Error)	91	19269.87	211.76	
Total	111	75143.70		

$\sigma_e^2 \doteq 477.86$

** = Significant at 1% Level
† = Significant at 2.5% Level

Table 22

INTERMEDIATE DATA FOR ANALYSIS OF VARIANCE

Transport Loaded (TL) Therblig

Profiles $Y_{.j}$	1	2	3	4	5	6	7	8
	807.7	839.3	862.3	878.0	869.7	1001.6	1059.3	1067.2

Operators $Y_{i.}$	A	B	C	D	E	F	G	H
	373.5	581.1	594.0	506.8	603.1	614.6	571.6	491.7
		I	J	K	L	M	N	
		492.4	429.2	573.9	520.6	568.7	463.9	

$\bar{R}_{..} = 17.24$
$Y_{..} = 7385.1$
$Y^2_{ij} = 504{,}921.41$
$C.T. = 486{,}961.63$

O = 495,312.35 - C.T.
P = 492,275.86 - C.T.
OxP (Error) = 504,921.41 - O - P - C.T.
T = 17959.78

Position (D) Therblig

Profiles $Y_{.j}$	1	2	3	4	5	6	7	8
	284.5	326.8	315.4	346.4	304.1	319.0	309.6	250.0

Operators $Y_{i.}$	A	B	C	D	E	F	G	H
	136.1	84.9	155.0	208.4	219.8	232.9	173.7	148.8
		I	J	K	L	M	N	
		160.3	170.1	169.8	186.9	241.9	171.2	

$\bar{R}_{..} = 18.10$
$Y_{..} = 2459.8$
$Y^2_{ij} = 59228.86$
$C.T. = 54{,}023.36$

O = 56,784.14 - C.T.
P = 54,415.33 - C.T.
OxP (Error) = 59,228.86 - O - P - C.T.
T = 5205.5

Table 22 (Continued)

Assemble (A) Therblig

Profiles $Y_{.j}$	1	2	3	4	5	6	7	8
	1000.4	1307.6	1405.8	1635.9	1603.0	1598.3	1559.0	1588.1

Operators $Y_{i.}$	A	B	C	D	E	F	G	H
	706.5	900.2	939.2	891.8	902.7	1086.3	945.7	719.4
		I	J	K	L	M	N	
		854.4	660.1	816.2	706.6	825.9	743.1	

$\bar{R}_{..}$ = 65.1   O = 1,244,901.47 - C.T.

$Y_{..}$ = 11,698.1   P = 1,245,698.20 - C.T.

Y^2_{ij} = 1,285,162.87   OxP (Error) = 1,285,160.87 - O - P - C.T.

C.T. = 1,221,835.21   T = 63,327.66

Position and Assemble (P+A) Therbligs

Profiles $Y_{.j}$	1	2	3	4	5	6	7	8
	1284.9	1634.4	1721.2	1983.3	1908.1	1916.5	1868.6	1842.1

Operators $Y_{i.}$	A	B	C	D	E	F	G	H
	842.6	985.1	1094.2	1100.2	1123.5	1318.2	1120.4	868.2
		I	J	K	L	M	N	
		1014.7	830.2	986.0	893.5	1067.8	914.5	

$\bar{R}_{..}$ = 67.3   O = 1,820,371.88 - C.T.

$Y_{..}$ = 14,159.1   P = 1,815,504.00 - C.T.

Y^2_{ij} = 1,865,144.71   OxP (Error) = 1,865,144.71 - O - P - C.T.

C.T. = 1,790,001.01   T = 75,143.70

II--Regression Analysis

The preliminary steps followed that of the analysis of variance technique outlined above. For the remainder of the regression analysis, the data used were based on the position-and-assembly (P+A) times for parts Nos. 2, 3, 4, 5, and 6.

The general equation for a linear regression curve is of the form: $\hat{Y}_x = b_0 + b_1 (X_j - \bar{X})$, where b_0 is the mean of the dependent variable (Y)., b_1 the slope of the linear regression line, and $\bar{X}$ the mean of the independent variable (X). By use of a regression line, the source of variance, due to the profile effect, can be separated into (1) that due to linear regression and (2) that due to departure from linear regression.

Related constants η^2 and r^2 give the percentage of variation in Y which can be accounted for by a regression curve through the means of each column, and the percentage of variation which is accounted for by the regression line used, respectively.

1. Computation of Eta - Squared (η^2)

$$\eta^2 = \frac{\text{Profile S.S.}}{\text{Total S.S.} - \text{Operator S.S.}}$$

where S.S. = The appropriate sum of squares from the analysis of variance table.

Example: $$\eta^2 = \frac{6224.51}{36578.25 - 18124.00}$$

$$= \frac{6224.51}{18454.25} = 0.34$$

2. Computation of Correlation Coefficient Squared (r^2)

$$r^2 = \frac{\text{Due to regression S.S.}}{\text{Total S.S. - Operator S.S.}}$$

Example: $r^2 = \dfrac{4350.19}{18434.25} = 0.24$

3. Computation of sum products of X and Y $[SP(XY)]$

$$SP(XY) = \frac{\left[N \sum {}_yT_{\cdot j}\, X_i - {}_xT_{\cdot\cdot}\; {}_yT_{\cdot\cdot}\right]}{N}$$

Example: $SP(XY) = \dfrac{[70(28373.8) - (9163.5)\ (224)]}{70}$

$$= \frac{-66458.0}{70} = -949.40$$

4. Computation of slope of regression line (b_1)

$$b_1 = \frac{SP(XY)}{SS(X)}$$

Example: $b_1 = \dfrac{-949.40}{207.20} = -4.78$

5. Computation of sum of squares due to regression

$$\text{Due to reg.} = b_1{}^2 \cdot SS(X) = \frac{[SP(XY)]^2}{SS(X)}$$

Example: Due to reg. $= \dfrac{(-949.40)^2}{207.20} = 4350.19$

6. Computation of sum of squares for deviation from regression

Dev. from reg. = Profile S.S. - Due to reg. S.S.

Example: Dev. from reg. = 6224.51 - 4350.19 = 1874.32

Table 23

REGRESSION ANALYSIS

Analysis of Variance Table for Regression

Position-and-Assemble (P+A) Therbligs

Source of Variation	df		SS	MS	F_c
Profile	4		6,224.51	1,556.13	6.62**
Due to reg.		1	4,350.19	4,350.19	18.45**
Departure from reg.		3	1,874.32	624.77	2.66#
Operator	13		18,124.00	1,394.15	
O x P (Error)	52		12,229.74	235.19	
Total	69		36,578.25		

** Significant at 1% level

\# Not significant at 1% level of significance and therefore can assume linearity of regression

$\eta^2 = 0.34$ $r^2 = 0.24$

Table 24

INTERMEDIATE DATA FOR REGRESSION ANALYSIS

Profile	2	3	4	5	6	
X_i	6	4	3	2	1	
$y^T{}_{i\cdot}$	1634.4	1721.2	1983.3	1908.1	1916.5	$y^T{}_{\cdot\cdot} = 9163.5$
$x^T{}_{\cdot j}$	84	56	42	28	14	$x^T{}_{\cdot\cdot} = 224$
$n_i\ X_i^2$	504	224	126	56	14	$\sum_i X_i^2 = 924$
$y^T{}_i(X_i)$	9806.4	6884.8	5949.9	3816.2	1916.5	$\sum_i y^T{}_i X_i = 28373.8$
$\bar{Y}$	116.7	122.9	141.7	136.3	136.9	

$Y_{\cdot\cdot} = 9163.5$ O = 1,217,691.60 - C.T.

$Y_{ij}^2 = 1,236,145.85$ P = 1,205,792.11 - C.T.

C.T. = 1,199,567.60   OxP (Error) = 1,236,145.85 - O - P - C.T

Total 36,578.25

SS(X) = 207.20

SP(XY) = -949.40

Profile	1
X_i	∞
$y^T{}_{i\cdot}$	1284.9
$\bar{Y}$	91.7

APPENDIX E

EQUIPMENT SPECIFICATIONS

Kymograph	6 channel constant speed tape recorder 115 volt Lafayette Instrument Company
Counter	Model B - 120506 6 digit reset counter 110 volts Veeder-Root, Inc.
Turntable	Model VLW13 Gear Reductor Gear Ratio 16:1 Boston
Variable Speed Drive	Type 29MR5 115/230 volt 0-220 R.P.M. Graham Transmission, Inc.
Micro switches:	
Counter circuit	Model GRL-5 SPST
Detection circuit	Model BZ--2RW82 SPDT Contact ratings: 10 amps at 125 volts Micro Switch - Division of Minneapolis-Honeywell
Proximity Device:	
Relay	Series 200 AC Relay Contact Type G 6 volt coil Guardian Electric Manufacturing Co.
Transformer	Filament Transformer P-6134 117 volt primary; 6.3 volt secondary Chicago Standard Transformer Corp.
Glaswitch	E-5600 Dry-Reed Switch SPST operated by external magnetic field 10 watt AC load at 115 volts The Revere Corporation of America
Magnet	Hyflux Alnico VI 3/4" x 5" Indiana Steel Products Company
Photo Electric Relay:	
Relay	Type 30 Relay using 925 Photo Cell 117 volt Campus Electronic Shop, Purdue University
Light source	6-8 volt - 6 candle power bulb General Electric Corp.
Transformer	Filament Transformer P6134 117 volt primary; 6.3 volt secondary Chicago Standard Transformer Corp.

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